THE APPLICATION OF RADIANT HEAT

to

METAL FINISHING

A Critical Survey of the Infra-red Process for the Stoving of Paints and Enamels

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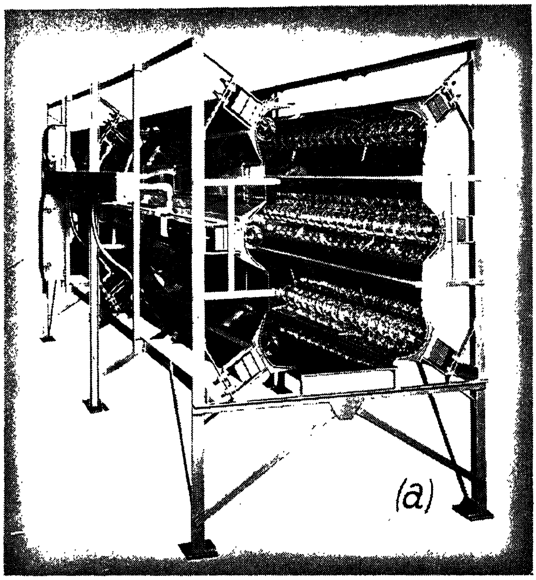

(*a*) "Infra-red" lamp heating plant for ammunition boxes 17 ft. long, consisting of two opposing banks of troughs with 306 lamps. Loading $76\frac{1}{2}$ kw.
(Courtesy of the General Electric Co., Ltd.)

(*b*) "Infra-red" lamp heating plant, 42 ft. long, containing 1,008 lamps for the drying of paint on petrol cans. Loading 252 kw.
(Courtesy of the General Electric Co., Ltd.)

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A Critical Survey of the "Infra-red" Process for the Stoving of Paints and Enamels

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AUTHORS' PREFACE

In presenting this book to the public the authors do so in the full realisation that the subject is one which is still very much in a state of flux. It cannot therefore be considered to represent the last word on the use of radiant heat in the stoving of organic finishes. Much work remains to be done, and even the question of the relative merits of gas or electricity for heating is still a subject of controversy. Nevertheless so much interest has been aroused in the possibilities of radiant heating, particularly by the so-called "infra-red" process using tungsten filament bulbs as the source of energy, that the authors feel that this account will serve a useful purpose. This is particularly the case, because there are a great many misconceptions about the whole subject, due in part to the mystifying use of the term "infra-red"; some of the published information has also been misleading, and exaggerated claims have been made for the possibilities of the process. Much of the authoritative literature is not readily accessible and sometimes is highly mathematical. Mathematical treatment has been reduced to a minimum in this volume, but an account of the fundamental theory has been included for those readers who may be interested.

In view of the fact that some of the less restrained of the articles which have appeared on the subject of "infra-red" heating, both in this country and in the U.S.A., have been sponsored by interests concerned with the sale of plant, it may perhaps be worthy of mention that the present authors write mainly from the standpoint of the user who is concerned with the installation of efficient metal-finishing plant and processes, and are not associated with the manufacturers of any particular type of plant.

The rapid introduction of electric radiant heat plant for paint drying in this country and in the U.S.A. has probably been largely due to the war situation. The demand arose for speed in the drying of painted parts, cost being a secondary consideration. It is here that "infra-red" scored, inasmuch as it enabled drying times to be cut to a fifth or less of the time taken in the usual type of gas-heated, convection oven. It was soon found, however, that although the demand for speed was met, both the initial cost of the plant and the actual production costs were relatively high. The new gas-heated plants are more economical in this respect, but the convection oven is perhaps still the cheapest method of paint drying, although other factors which cannot be classed as direct operating costs often militate strongly in favour of radiant heating.

Nonetheless, the advent of the radiant heating unit has had a profound effect on the whole question of industrial oven design, and whatever the future tendency, there can be no doubt that the experience gained as a result of its introduction will be of great value to industry as a whole. With increasing attention being paid to heat conservation and economy a great deal of progress is constantly being made, so that these processes will certainly have their place in peace-time production. Radiant heat is not, however, a universal panacea for the metal-finishing industries, and there will still be many applications in which the convection, or a convection-cum-radiation oven will find its place, although there will undoubtedly be radical improvements in the design of such ovens. For these reasons the fundamental principals of radiation plant design, paint formulation, etc., have been stressed especially in the ensuing pages as future development must inevitably depend on the due appreciation of these factors irrespective of any particular features of plant design.

The authors wish to express their appreciation for valuable help and guidance given to them in the course of discussions with firms and individuals too numerous to mention, and representing gas and electrical equipment manufacturers, paint suppliers, plant construction engineers, and many others. In particular, thanks are due to the General Electric Co., Ltd., the British Thomson-Houston Co., Ltd., the Birmingham Corporation Gas Department Industrial Research Laboratories, and the Gas, Light and Coke Co., Ltd., for information and permission to reproduce illustrations, and to Messrs. Lewis Berger and Sons, Ltd., for their helpful co-operation on the paint side of the problem. Thanks also are due to the Directors of Messrs. Joseph Lucas, Ltd., for permission to publish this volume, which is the result of investigations on radiant heat and paint finishing processes carried out on behalf of the company.

Finally, the authors are grateful to Messrs. Industrial Newspapers, Ltd., for permission to reproduce much of the material on which this book is based, and which originally appeared as a series of articles in *Sheet Metal Industries*.

J. H. Nelson
H. Silman

Joseph Lucas Research Laboratories
Birmingham

August 1943

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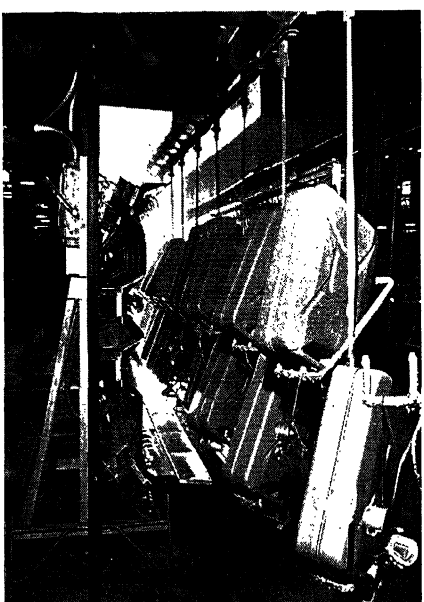
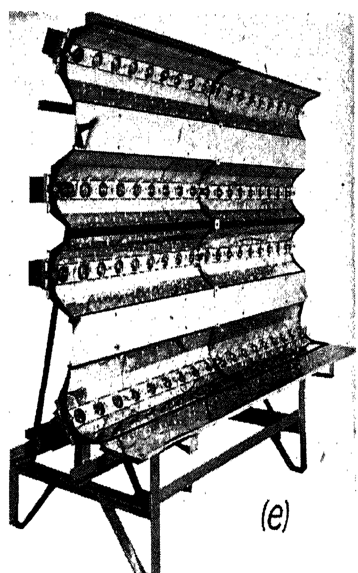
FRONTISPIECE (*c*), (*d*) AND (*e*)

(*c*) "Infra-red" lamp heating plant for drying paint on ammunition boxes. The plant is 9 ft. long and contains 378 lamps. Loading $94\frac{1}{2}$ kw.
(Courtesy of the General Electric Co., Ltd.)



(*d*) Petrol cans entering plant illustrated in Frontispiece (*b*)
(Courtesy of the General Electric Co., Ltd.)



(*e*) 6 ft. "Infra-red" heating unit.
(Courtesy of the General Electric Co., Ltd.)

INTRODUCTORY

The increasing application of the stoving paints and enamels in industry has resulted in a demand for a more rapid method of baking such finishes than could be achieved in the convection oven. As a result of this demand there has been a great deal of interest in the possibilities of using radiant heating methods for facilitating the high temperature stoving operation necessary for obtaining the maximum durability from these enamels. Many of the plants which have been designed make use of tungsten filament bulbs as the source of radiant heat, and the term "infra-red" has been widely applied to the type of radiation responsible for the paint-drying process.

The authors dislike this term, since it implies that there is something distinctive about the radiation responsible for the drying action. Actually the precise nature of the radiation used has little or no influence on paint-drying phenomena. The only consideration is the rate at which the paint film heats up, and this is determined by the total energy input from the source of heat. All heating by radiation whatever the nature of the source, is largely dependent on radiation of those wave-lengths situated in the infra-red region of the spectrum and longer than those normally visible to the human eye, i.e. wave-lengths longer than about 7,000 Å. For these reasons the term "infra-red" will be avoided as far as possible in the ensuing pages.

There is nothing fundamentally new about the utilisation of radiant energy for heating purposes. The fact that radiation can be directly transmitted through air without increasing the temperature of the latter has

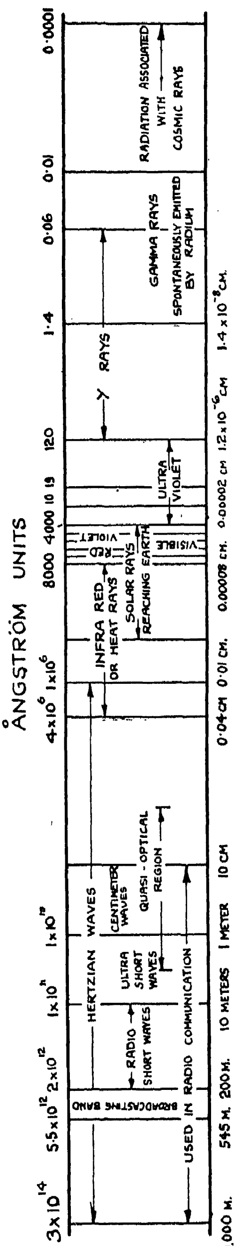


Fig. 1.—The Ether Spectrum

been known for a long time. Yet in the main the drying of paints and lacquers in the metal-finishing industries has been almost universally carried out in a convection oven. In this type of oven a chamber is heated up to the drying temperature by gas burners or by some other suitable means and the parts to be dried are put into it. Naturally the heating up of the paint film by conduction and convection is slow, and the drying time is correspondingly long.

Advantages of Radiant Heating.—By radiation it is possible to convey a great deal of energy to the surface being heated very quickly and simply. Probably the reason for the delay in the general introduction of radiant heating in industrial metal-finishing processes was due in part to the innate conservatism of industry, the relatively high cost of radiant heating plant of this type, and other factors which will be discussed later. Furthermore, in the case of lacquers and varnishes dried largely, if not entirely, by solvent evaporation, a convection oven functioned quite satisfactorily. Only comparatively low temperatures were required and the through current of air served to remove the solvent vapours quickly. With the introduction of the oil-modified synthetic resin varnishes and paints, however, hardening of the film had to be brought about mainly by means of polymerisation processes accelerated by heat. It therefore became necessary to raise the paint film to a relatively high temperature, i.e. of the order of 300–350° F. To do this in a convection oven was a lengthy procedure and, moreover, the oven had to be heated up considerably ahead of the time when the work had to be put into it in order that the necessary temperature should be reached. It was soon realised that these finishes were especially suited for drying by radiant energy, and many plants have already been installed, making use of radiant heating, not only for the drying and hardening of enamels and varnishes, but for many other purposes as well.

A number of examples of the reduction in the baking time of paints that has been effected on U.S. Military equipment by the use of radiant heat are given by Cusack(1), and Table I is based on the result obtained.

A great deal of development will naturally have to be done from the point of view of both radiator design and paint formulation to suit the special conditions. A certain amount of this investigatory work has been carried out, and on a basis of results obtained to date, many plants are operating extremely successfully. By means of radiant heating it has proved possible to stove lacquers which formerly took an hour or an hour and a half to finish in the convection oven in a period of six or eight minutes. There is little doubt that with improvement in oven design and in paint formulation, this time will be even further reduced. Another advantage of the method is that drying takes

TABLE I

COMPARISON OF PAINT BAKING BY CONVECTION AND RADIATION

Coating.	Main Constituent.	Uses.	Stoving Temp. °F.	Drying-time.	
				Convection.	Radiation.
Zinc chromate primer	Glyceryl phthalate	Corrosion inhibiting primer	160	90 mins.	30 secs.–1½ mins.
Rust inhibiting primer	,,	Army vehicles, tanks	200	30 mins.	4½ mins.
Lacquer for ammunition	Nitro-cellulose	Protection and identification	180	15 mins.	30–40 secs.
Acid proof black	Bituminous	Inside coating on shells, bombs and land mines	180	30 mins.	4½ mins.
Camouflage lacquer	Nitro-cellulose	Over primer	180	10 mins.	30–40 secs.
Aircraft enamel	Glyceryl phthalate	Exterior fabric and metal aircraft parts	300	15 mins.	8 mins.
Black enamel	,,	Aircraft engine castings and instruments	300	15 mins.	8 mins.
Dull olive drab	,,	Army vehicles, tanks, cars	250	60 mins.	4½ mins.
Stencilling enamels	,,	Lettering on exposed surfaces	200	30 mins.	3 mins.

place by polymerisation rather than oxidation, due to the extremely rapid rate of heating; this has a favourable influence on the paint finish which will tend to have greater durability than would otherwise be the case.

In the present survey it is proposed to deal with the fundamental principles involved in the application of radiant heating to metal-finishing processes, so far as it has developed to date. The whole subject is still in a transition stage, and rapid developments are to be expected in the very near future.

CHAPTER II

PRINCIPLES OF HEAT TRANSFER

Theory of Radiation.—The processes involved in radiant heating differ fundamentally from those of convection and conduction, and thus merit careful study. The transference of heat by radiation depends almost entirely on the radiator and receiver; any reflector, of course, is considered as part of the radiator. The intervening medium, which is all-important from the point of view of conduction and convection, is not only unnecessary for the efficient transference of radiation, but, in that it absorbs some of the radiant energy, is definitely disadvantageous. It is, in fact, possible to obtain more efficient radiant heating in a vacuum than in open air. Actually, the energy lost by absorption is very small and can, for all practical purposes, be neglected. Realisation of this fact has led to the erroneous conclusion that the influence of the intervening air is of no importance. The moment the temperature of the receiver begins to rise it starts to lose heat by convection; thus, although the air does not stop the radiant energy reaching the receiver, it will aid the very rapid loss of heat if due care is not taken. We shall return to this consideration when discussing the design of ovens for radiant heating.

Physical Laws.—The physical laws controlling the process of radiation differ from those controlling conduction and convection. Very approximately one can say that the transference of energy by conduction and convection depends upon the area involved and the difference in temperature. In the case of radiation the transference is proportional to the area, and to the fourth power of the temperature difference. Thus, for a given area, if the temperature difference from the surroundings is doubled, the heat energy lost by convection is doubled; on the other hand, that lost by radiation is increased sixteen times (see Figs. 2 and 3, p. 9).

The immediate deduction from this difference in behaviour is that if it is desired that as much energy should be transferred by radiation as possible, then the higher the temperature for a given area the better will be the result. The fact that we may provide for the use of the heat which the radiator may lose by conduction and convection, must not lead to the conclusion that the efficiency of radiation is unimpaired. Further, if we are concerned with the generation of radiant energy the enclosure of the source of radiation in a glass bulb will seriously reduce the convection and will allow the use of a small high temperature

source rather than a large low temperature one. In fact, it would seem, without examining the details of design, that the electric bulb is a very efficient source of radiant energy, and that it is improbable that any other radiator would be likely to be more efficient as a source of radiant heat.

General Considerations.—Before examining the physical laws controlling radiant heating in detail, it is worth while extending the general considerations that can be deduced from the simple expression of the laws given above. The difference in partition of the heat energy between convection and radiation has led to the use of a high temperature-small area radiator enclosed so that convection is confined to a limited volume and greatly reduced in efficacy. The effect on the design—or rather choice, since the article to be heated is designed without reference to whether it can easily be heated or no—of the receiver will be materially different. For example, in order to gather as much energy as possible the area of the receiver must be large, and if the temperature rise is to be rapid the mass must be small. In the case of the radiator it has been pointed out that the condition for efficient radiation is opposed to that for efficient convection, and thus the deleterious effects of convection could be eliminated to a very large extent. With the receiver the conditions are not so fortunate, and the conditions for rapid absorption of radiation are precisely those for rapid loss by convection. This fact may limit the choice of receiver, but apart from this, it is possible to draw two conclusions of a general nature. Firstly, the energy must be radiated on to the receiver at as high a rate as possible so that the loss by convection is limited. This may be termed the adiabatic effect. Secondly, the surrounding air should be kept at as high a temperature as possible so that the receiver will not tend to lose heat until it has reached the air temperature. To maintain the air temperature, heat lost by the receiver should be conserved and the movement of the air restricted. It is important to notice that both these conclusions can be turned to use in the application of radiant heating. In fact, the principal reason for using radiant heating for the drying of paint is the possibility of rapid heating, and the conservation of the heat lost by the receiver will further increase the rapidity of the temperature rise by providing an air temperature above that of the receiver at the commencement of heating.

Radiant heating can therefore best be applied to articles having relatively small heat capacity for their area and requiring very rapid heating to a temperature not greatly in excess of their surroundings. Articles needing slow heating or heating to a temperature very much above the surroundings are not suitable, unless radiators capable of large outputs are available.

Evaporation.—At this point it seems worth while mentioning the particular case of evaporation. This is a process that takes place at a constant temperature—that is the boiling-point of the liquid cannot be exceeded—but which requires a definite and generally large amount of heat energy. For simplicity let us treat the case of water. Two things must be done; firstly, the heat energy necessary to transform the water from the liquid to the gaseous phase must be provided and secondly, the vapour so formed must be removed from the immediate vicinity of the liquid. Radiant energy can be used to perform the former requirement, but a flow of air is necessary for the latter. Now the capacity for the removal of water vapour by a given flow of air will depend upon its relative humidity and temperature. The most efficient removal of water vapour will thus be effected by warm dry air. The sequence of events should thus be: (*a*) to heat the air so that it has a large capacity for the removal of water vapour, (*b*) to pass the air in this condition over the article to be dried (at the same time supplying the heat required for evaporation), and (*c*) to remove the water-laden air. Now whilst radiation may play its part in such a process it certainly would not be ideal to depend solely on radiant heating of the article to be dried, because in this case the air would not be pre-heated and thus would arrive at the wet object with a lower capacity for water than could be attained by pre-heating.

Phenomena of Heat Transference.—The fact that in any practical problem it is impossible to separate completely the effects of radiation, conduction and convection, does not mean that it is incorrect to consider one process in isolation. In fact for the complete understanding of the phenomena of heat transference it is necessary to examine each alone and in detail, and finally, the combined effects of all three. This procedure makes the assumption that each effect is independent of the other. The independence of radiation from conduction and convection is fundamental. Radiation depends upon the emission of quanta of energy probably from the interstices of the atom or molecule, while both conduction and convection depend upon physical collisions between molecules. Thus we can consider the laws of radiation in isolation, but conduction and convection cannot, at first sight, be so easily separated since they both depend upon the same fundamental process. The natures of the two processes tend to separate themselves in practice. For example, in a medium such as air the effect of convection is so large that when we wish to study conduction it is necessary to go to considerable trouble to eliminate convection. With solids, of course, convection does not arise and we have pure conduction to deal with. These are the extremes and although many cases exist where both effects are operative they do not concern the problem of

heating solid articles; the heating of liquids, especially liquid metals and liquids of high viscosity, is of course the field where the combined effects of conduction and convection will produce special problems.

For the present consideration of heat transference radiation can be treated as a process that is independent of any medium, needing only a radiator and a receiver; convection is the method of heat transference through a gas, the heated gas being moved bodily and replaced by cold gas, which in turn is heated; finally, conduction is the method of heat transference in solids, the whole of the body tending to reach a mean temperature rather than one part remaining at a higher temperature than the rest.

Laws of Heat Transfer.—The laws of heat transference by radiation have been the subject of the most extensive study, both because of their importance in understanding and increasing the production of light and because of their importance in connection with the knowledge of the nature of the atom. It has been stated above that the energy radiated by a body depends upon the fourth power of the temperature. This law was first enunciated by Stefan and may be more exactly stated by the expression:

$$Q = A.S.c. (T_1^4 - T_0^4)$$

where Q is the quantity of heat energy radiated,

T_1 the temperature of the radiator,

T_0 the temperature of the surroundings, both these temperatures being expressed on the Absolute scale on which the freezing-point of water is $\begin{pmatrix} 273^\circ \text{K.} \\ 520^\circ \text{Abs.F.} \end{pmatrix}$ instead of the customary $\begin{pmatrix} 0^\circ \text{C.} \\ 32^\circ \text{F.} \end{pmatrix}$

S is the area of the radiating surface.

c a constant equal to $1 \cdot 27 \times 10^{-12}$ cal. sec.$^{-1}$ cm.$^{-2}$

and A the emissivity of the surface.

The implications of the law as stated are that all surfaces are radiating all the time and a net heat transference is only obtained when there is a difference in temperature between the radiator under consideration and its surroundings. The fact that the radiation is going on all the time is important because it must be realised that one cannot stop energy being radiated; one can only ensure that the incident energy is sufficient to stop transference. A further important point is implied by the factor A, the emissivity of the surface. This means that some surfaces will be more efficient radiators than others and further, that some surfaces will be better absorbers than others.

Heat Emission by Radiating Surfaces.—The coefficients of absorption and emission can be shown by experiment to be equal, so that a poor radiator will be a poor receiver, and a good radiator a good receiver. The ideal surface is thus a black one, that is one that absorbs

all the incident energy, and will thus radiate the maximum amount of energy for a given temperature. The "black body" radiator can be studied theoretically and it is possible, not only to state how much

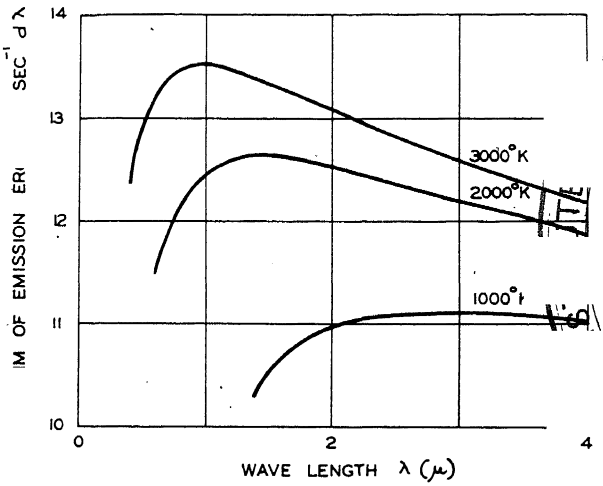


Fig. 2.—Spectral energy distribution of "black body" radiation (logarithmic scale)

total energy will be radiated at any given temperature, but also the way in which the energy is distributed with regard to wave-length (see Figs. 2 and 4).

Real radiators differ from the ideal both with regard to the total quantity of energy radiated and also with respect to the spectral distribution of the energy. The carbon filament behaves very nearly as a black body, but the tungsten filament has a total emissivity of between 50 per cent and 60 per cent and further, emits relatively more radiation in the visible region than in the infra-red as compared with the theoretical "black body". The practical result of the low emissivity is that a tungsten wire must be raised to a higher temperature than a black body for a given output of radiation, and while the melting-point of tungsten will set a limit to the temperature that can be used, the high temperature will not in itself be a cause of inefficiency. In fact the data in Table II shows that the electric lamp is a very efficient radiator indeed.(²)

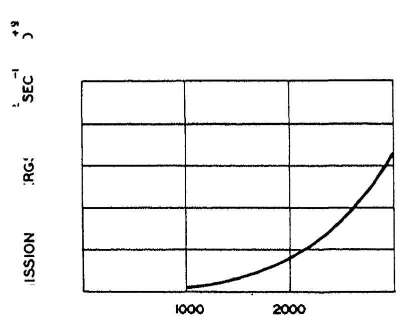


Fig. 3.—Relation between energy emitted per unit area and temperature

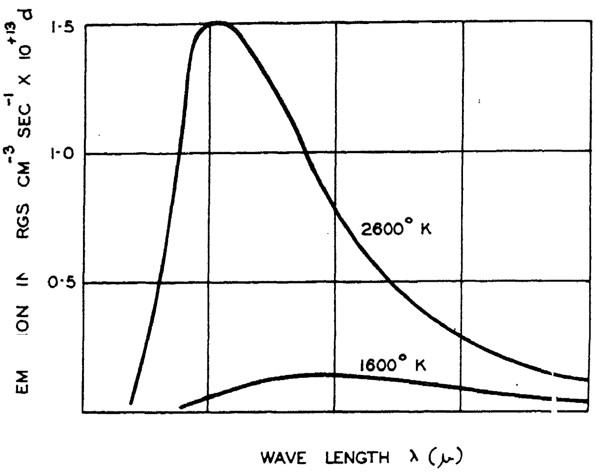


Fig. 4.—Spectral energy distribution of "black body" radiation

TABLE II

The Standard Electric Lamp. Heat lost by Conduction, Convection and Radiation

Method of Heat loss by Filament.	Percentage of Energy input lost.	
	Vacuum Bulb.	Gas-filled Bulb.
Convection	0	20
Conduction along leads and supports . .	8	5
Total local heating	8	25
Infra-red radiation	86	67
Luminous radiation	6	8
Total radiant heat	92	75

The electric bulb is so designed that the energy must either be emitted as radiation or cannot be lost at all; hence the emissivity is only of secondary importance. At the receiving end this state of affairs does not hold and the absorption coefficient of the article to be heated is quite important, since in this case the radiation is either absorbed or scattered and possibly lost.

Conduction and Convection.—The quantity of heat transferred across a unit area by conduction can be expressed by the relation,

$$dQ = K\frac{dT}{dx}$$

where K is a constant and $\frac{dT}{dx}$ the temperature gradient normal to the plane of the unit area under consideration. Thus the quantity of heat transferred will depend upon the temperature difference directly.

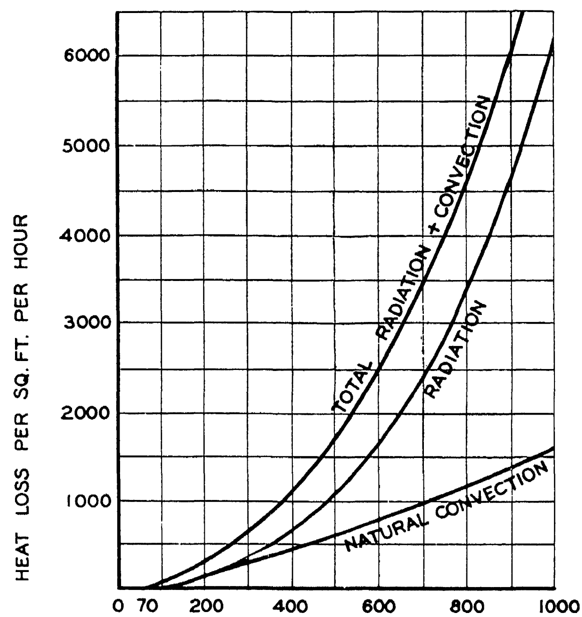


Fig. 5.—Energy losses from a heated surface

The rate of transfer of heat by convection is not subject to such exact formulation. The quantity of heat lost by a unit area in contact with a gas at a lower temperature depends upon whether the flow of gas is streamlined or turbulent, and of course, an intermediate state will exist. Observation indicates that a condition of turbulence may be assumed in a radiant heating oven and so the empirical relation:

$$Q \propto T^{\frac{5}{4}}$$

should be used to represent the loss of heat per unit area by a surface at a temperature T° above the surroundings. Clearly the assumption that:

$$Q \propto T$$

will not result in any great error, providing the difference in temperature is small. Fig. 5 shows the total heat loss from a surface analysed into

its components of radiation and convection and Fig. 6 the influence of emissivity on the heat lost by radiation.

Work of Tiller and Garber.—Recently Tiller and Garber (3) published a theoretical treatment of radiant heating, in which they relate the temperature attained to the surrounding air temperature, the absorption and the energy incident.

A rigorous theoretical treatment of the combined effects of absorption of radiation and losses by radiation and convection is not possible in a general case. The assumptions made in Tiller and Garber's treatment are such that the problem is very much simplified, without being made too ideal, and at the same time experimental results show that the conclusions reached are at least approximately correct.

The following assumptions are made concerning the articles heated and the mechanism of radiant heating:

(1) Articles are of thin sheet metal, between 12 and 28 gauge.
(2) The distribution of radiation is uniform.
(3) The temperature distribution is uniform, when edge effects are neglected.
(4) The heat loss by re-radiation is negligible.
(5) Energy is used only for heating and not for evaporation or chemical action.
(6) The heat lost by convection is proportional to the difference in temperature between the article and the surrounding air.

The following symbols are used:

A = absorptivity of stock, or ratio of radiant energy absorbed and converted to heat to incident radiant energy, dimensionless.
c = specific heat of stock, B.t.u./(lb.) (° F.).
h = convectional coefficient of heat transfer during radiant heating B.t.u./(hr.) (sq. ft.) (° F.).
h_c = convectional coefficient of heat transfer during cooling, B.t.u./(hr.) (sq. ft.) (° F.).
I = intensity of radiant energy incident to surface of stock, watts/sq. ft.
k = factor to convert electrical energy to thermal heat, 3·41 B.t.u./(watt) (hr.).
K = ratio h/c L, 1/hr.
L = thickness of stock, ft.
m = mass of stock per unit area, lb. sq./ft.
P = performance ratio of radiant heating, or ratio of sensible heat retained by stock to radiant energy incident to surface, dimensionless.
T = variable temperature of stock, ° F.

T_o = initial temperature of stock, ° F.
T_a = temperature of air, ° F.
T_c = temperature attained by stock upon cooling, ° F
T_{co} = initial temperature of stock at start of cooling, ° F.
T_m = maximum temperature attainable by stock, ° F.
ρ = density of stock, lb./cu. ft.
θ = time, hr.

If a thin sheet metal object of unit area, thickness L, density ρ, specific heat c, and having an absorption coefficient A is exposed to an intensity of radiation I, in an atmosphere having an air temperature T_a, then, in time $d\theta$,

$$kAId\theta = c\rho LdT + h(T - T_a)d\theta \qquad (1)$$

$$\text{i.e. Heat absorbed} = \frac{\text{Heat used in raising}}{\text{temperature of article}} + \frac{\text{Heat lost by}}{\text{Convection.}}$$

The direct integration of this expression involves the further assumption that all factors other than θ and T can be kept constant. This again is not true of industrial practice, but it can be attained experimentally, and moreover, does not represent an over-idealised state on which to draw general conclusions.

The expression (1) can be re-written:

$$\frac{dT}{d\theta} = \frac{kAI}{c\rho L} - \frac{h(T - T_a)}{c\rho L} \qquad (2)$$

Under any given set of conditions of radiation and convection the sample under test will tend to attain a steady temperature. This will be the maximum temperature, T_m, and will be attained when

$$\frac{dT}{d\theta} = 0$$

$$\text{i.e. } kAI = h(T_m - T_a)$$

$$\therefore \quad T_m = T_a + \frac{kAI}{h} \qquad (3)$$

This expression is very important since it implies that the maximum temperature attainable by any article under a given set of conditions, is determined only by the absorption of the surface of the article. Thus, within the limits of the original assumptions, the maximum temperature attained is independent of the mass of the article. Further, the importance of the temperature of the surrounding air is shown, and it is clear that any heat energy which cannot be used in heating the article directly should be used in heating the surrounding air.

It seems worth while stating at this point that experiments indicate that the implications of expression (3) are sensibly true in practice. When the conditions are very considerably different from those

assumed, the maximum temperature is very nearly independent of the mass. For example, two blackened copper sheets, one having a thickness ten times that of the other, were heated one after the other in a small enclosure. The maximum temperature attained was 306° F. in the case of the thick sheet and 298° F. in the case of the thinner one. Further, when the results were analysed it could be shown that the experimental figures calculated were in conformity with what would have been expected under the conditions assumed in this theory. Figs. 6, 7, 8 and 9 are nomographs showing the application of these principles in practice.

Expressions (2) and (3) can be rewritten as

$$\frac{dT}{d\theta} = \frac{h}{c\rho L}(T_m - T),$$

which on integration leads to

$$T = T_m - (T_m - T_0)e^{-\frac{h\theta}{c\rho L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

when T_0 is the temperature of the article on entering the oven.

Heat loss by the article on leaving the oven can be treated in exactly the same way and leads to the expression

$$T_c = T_a + (T_{co} - T_a)e^{\frac{h\theta}{c\rho L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The efficiency of utilisation of the energy can be gauged from values of the performance ratio, P, which is defined as the ratio of the heat retained to that incident on the article. Thus

$$P = \frac{c\rho L(T - T_0)}{kI\theta} \quad . \quad . \quad . \quad (6)$$

This expression can be re-written as

$$P = A\left(\frac{T_m - T_0}{T_m - T_a} \quad \frac{1 - e^{-\frac{h\theta}{c\rho L}}}{h\theta/c\rho L}\right. \quad (7)$$

When $\theta = 0$ expression (7) reduces to

$$P_0 = A + \frac{h(T_a - T_0)}{kI} \quad (8)$$

This expression shows that the initial performance ratio depends very considerably on the air temperature T_a. Thus not only is the air temperature important because of its influence on the maximum temperature attained but also because it affects the efficiency of utilisation of the energy and thus the rate of heating of the articles in the oven.

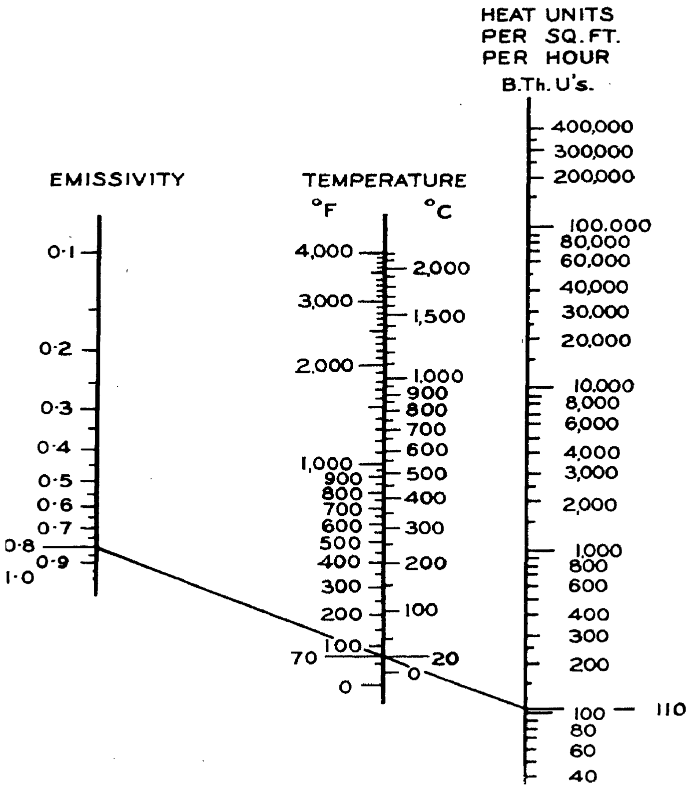


Fig. 6.—Nomograph for radiation emitted by hot surfaces

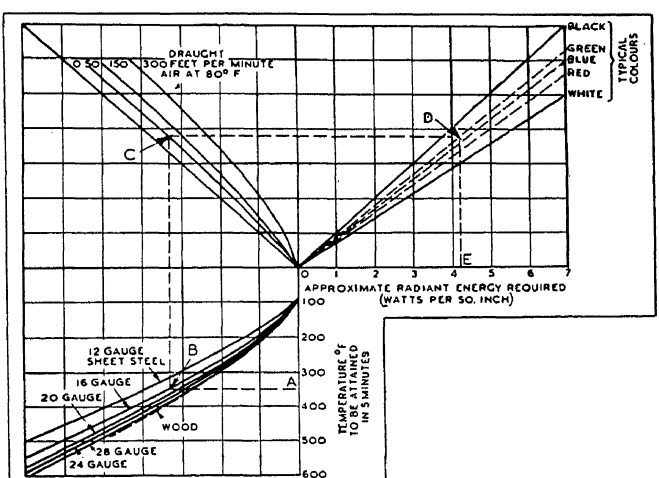


Fig. 7.—Energy requirements for paint baking
(Illum. Eng. (1941), *36*, 61)

While the above theoretical treatment assumes a set of idealised conditions, the original work shows that it is applicable to experimental results and further confirmation of the essential validity of the conclusions has been obtained by the present authors.

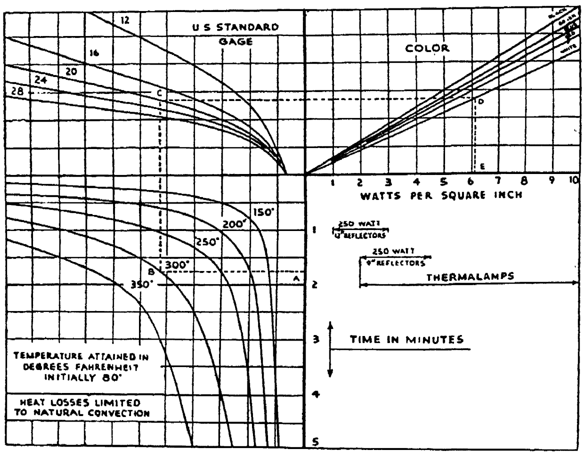


Fig. 8.—Energy requirements for paint baking (C. M. Hall Mnf. Co.)

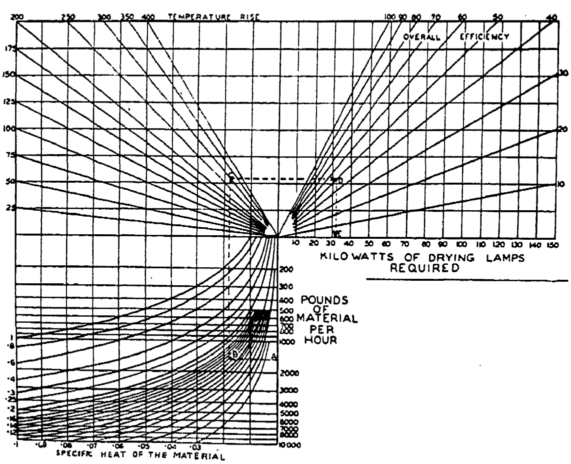


Fig. 9.—Energy requirements for mass heating (Illum. Eng. (1941), *36*, 61)

Theoretical Conclusions.—Summarising the results of this theoretical treatment of radiant heating we can say that the simple theory of radiation as expressed by Stephan's law teaches that rapid heating and efficient use of the available energy require high values of the radiant energy and high absorption coefficients. The treatment of Tiller and Garber shows that the surrounding air temperature is of major

importance and that it will influence both the rate of heating and the final temperature attained.

From the point of view of the design of equipment, the considerations of theory lead to three rules which should be borne in mind as being of fundamental importance:

(*a*) For efficient heat transfer, the temperature difference between the source and the work must be as high as possible.

(*b*) Since the quantity of heat transferred by radiation depends on the fourth power of the temperature difference, and that by conduction and convection approximately directly as the temperature difference, radiation is the most efficient means of heat transfer.

(*c*) The air temperature in a radiant heating oven should be at such a level as to ensure the minimum transfer of heat by means other than radiation. The air temperature should be such that the transfer of heat to the work when it is colder than the surrounding air is equal to that lost by the work when it reaches a higher temperature.

THE HISTORY OF THE "INFRA-RED" PROCESS

The history of radiant heating in the metal-finishing industry is interesting as it shows how strongly the initial conditions under which a process is developed may influence the whole course of that development even when those conditions no longer apply. Radiant heating was initially employed as a method of repairing blemishes on car bodies, without dismantling the whole body and re-stoving. For such "touching-up" an open frame-work heating unit was needed and now, nearly ten years later, the same open frame-work is still in common use, although the conditions of application of the process have changed entirely.

Groven's Patent.—The original description of the use of radiant heat for the drying of paint was given by F. J. Groven(4) of the Ford Motor Company. In his patent application Groven explains that car bodies were hitherto finished with an air-drying colour varnish, the durability of which was not satisfactory. This colour varnish was superseded in part by enamel, but principally by lacquer. Both were superior to colour varnish in durability, but the enamel was far superior to the lacquer. However, durability alone could not be the deciding factor. The enamel needed prolonged stoving at 300° F. so that all bodies had to be finished before assembly of windows, door handles, etc., and before fixing to the chassis. Great care was taken to ensure that the enamel was not scratched, but a small number of bodies inevitably were damaged and had to be stripped of all attachments and removed from the chassis for re-enamelling. This process proved so expensive that the majority of cars were finished with lacquer, in spite of the fact that bodies so finished had to be hand polished.

Groven's patent is concerned with a method of repairing blemishes on enamelled bodies without dismantling the body (Fig. 10). Moreover, he uses the same enamel on the repaired panel as was used originally and the same number of coats are applied. The prolonged baking in an oven is replaced by a relatively short exposure to radiation from carbon filament lamps in gold-plated reflectors. Even when repairing a blemished door panel it is found unnecessary to remove the window glass, although the window should be wound up.

Groven finds that a similar result can be attained with the tungsten filament lamp, but not with a heated iron wire as a source of radiation. He does not attempt a full explanation of the effect, but covers in his

application the use of radiation mainly confined to the range of wave-lengths 0·6μ to 1·6μ. He does, however, suggest that the difference may be due to the mechanism of absorption of the radiation and gives a table of results for water which shows a considerable degree of selective absorption (see Table III). The difference in energy distribution is also shown in figures 2 and 4.

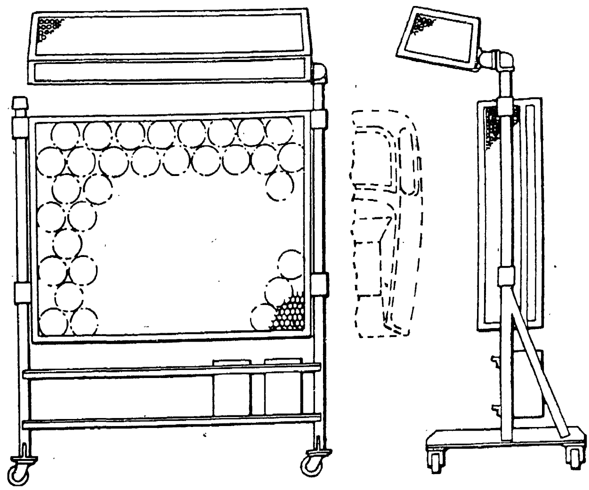


Fig. 10.—Early radiant heating unit (Groven)

TABLE III

TRANSMISSION AND ABSORPTION OF RADIATION BY WATER (GROVEN)

Source of Radiation	Iron Wire.		Carbon Lamp.		Tunsten Lamp.	
Temperature . .	1000° K.		2140° K.		3130° K.	
Depth	Trans.	Absorp.	Trans.	Absorp.	Trans.	Absorp.
Surface . .	—	96·9	—	65	—	35
1 mm. . .	3·1	2·0	35	14	65	6
2 mm. . .	1·0	0·35	28	7	59	5
3 mm. . .	0·65	0·10	24	4	54	2
4 mm. . .	0·55	0·05	22	2	52	1
5 mm. . .	0·5	—	20	—	51	—

Theoretical Deductions.—Groven then argues that the radiation from the carbon lamp is superior to that from the iron wire because it is not subject to such a high absorption at the surface, and because there is considerable absorption within the first millimetre—approximately the coating thickness. He says that enamel will behave in a manner very similar to water and thus the above argument can be

applied. He goes on further to say that the radiation from the tungsten lamp, which will penetrate further into water, will have no advantage over that from the carbon lamp, as the excess radiation will penetrate "through the enamel and even through the metal panel itself."

It is somewhat difficult to accept the close similarity between water and enamel that is put forward, but this does not mean that the argument is altogether false. In fact it is probable that the exact nature of the mechanism of absorption of the radiation is of importance in determining the wave-band to be used. Clearly, very rapid surface absorption, whilst the underlying layers are unheated, cannot be desirable, especially if the enamel film is of poor heat conductivity. Even the most minute penetration will give an entirely different effect, and it is probable that in this respect the reason given for the superiority of the carbon lamp over the iron wire is substantially correct.

The same cannot be said for the preference for the carbon as opposed to the tungsten lamps. Though there will be some penetration below the surface of the enamel the layer as a whole is more often than not likely to be opaque to radiation. Any question of the penetration of metal by the radiation cannot be entertained. The heat will be transmitted to the underlying metal and even conducted through it, but the radiation itself will never pass a thickness of metal strong enough to be self-supporting. Here Groven seems to fall into the trap of assuming that only the enamel layer itself is heated, while in another part of his description, he states specifically that it is necessary to wind up the window, because if left down it will become overheated and crack.

It is probable that it is necessary to consider the enamel and the underlying sheet metal as a single unit, which is heated as a whole. The radiant energy may be absorbed principally in the enamel layer and in the metal surface, but the temperature attained will be sensibly constant throughout owing to the high conductivity of the metal.

Practical Application.—Groven's original work was concerned with repairing blemishes, but it was obviously a short step to the application of the same process to the initial enamel coating. The first production successes were attained with the undercoats of the car bodies, the heating being insufficiently uniform for the finishing coat. In this application the tunnel method was not used, but each body was enclosed in a clam built in the same shape as the body and completely lined with radiant heating lamps and reflectors. The clam and body moved together on the conveyor so that the advantages of the conveyor principle were attained (Fig. 11).

The finishing coats of steering-columns were then dried in a tunnel of the now familiar form. Their cylindrical shape lent itself ideally to tunnel drying (Fig. 12).

In spite of the success attained in the Ford plant the new method of stoving did not immediately attain popularity. This was in part due to the fact that many finishes were not formulated in a manner suitable for drying by radiant heat; thus the paint manufacturers did not

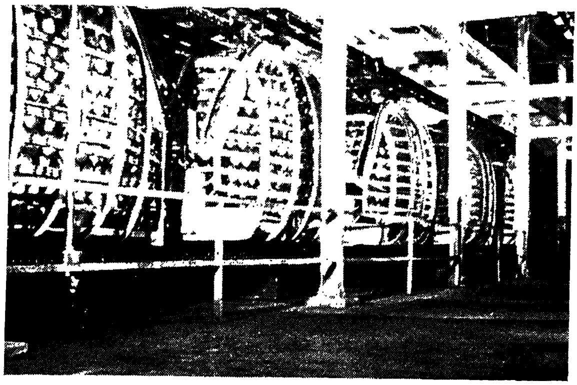


Fig. 11.—Clam-type oven for automobile bodies (Ford Motor Co.)

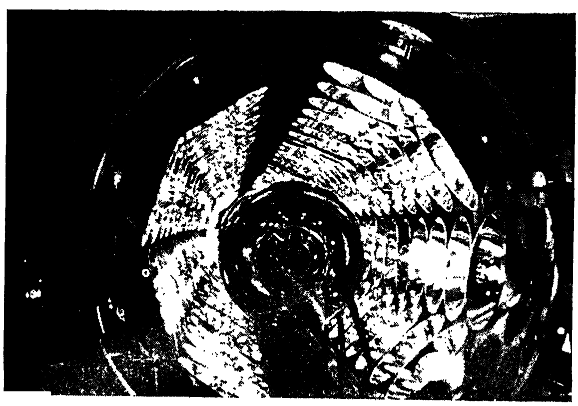


Fig. 12.—Tunnel-type oven for steering-wheels (Ford Motor Co.)

welcome the new process. The fact that the new equipment was manufactured by strangers to the paint trade will have had its effects, as neither equipment nor paint manufacturers were able to realise the possibilities of the process. The question of paint formulation will be discussed later.

In time, however, the load-building potentialities of radiant heating were appreciated by the power supply companies; at the same time it soon became evident that paints could be reformulated to give satisfactory results, and further, that in many cases the finish obtained was

superior to that given by the usual convection oven. The interest in the process then grew rapidly, but the design of the drying units remained almost entirely in the hands of the users and the suppliers of the electrical lighting equipment. The result of this has been that a great deal of attention has been given to the design of a suitable source of radiation and reflectors to control the radiation and very little to the conservation of the heat energy.

In fact it was at first thought that the radiation itself was contributing some effect other than the mere raising of temperature and that satisfactory results could be obtained by the use of the open type of oven, as the surrounding air was not heated appreciably. While there is a germ of truth in both these ideas, they are in reality very misleading. The fact that when a sheet metal plate is dried it is immaterial whether it is irradiated from the back or the front shows that the main effect of the radiation consists in bringing about a rapid temperature rise. This experiment has been extended still further and it has been shown that the same rates of paint drying can be attained in the conventional type of oven if the articles can be put through the required temperature cycle ([5]).

The effect of the surrounding air was also incorrectly interpreted. No amount of convection will have any influence on the absorption of energy by the article being heated, but as we have already seen it will have a serious effect on the temperature reached. To reach the same temperature far more radiant energy will therefore have to be applied. The situation thus called for two solutions, (*a*) conservation of energy, and (*b*) high energy density. The problem was therefore turned over to the illuminating engineer and an undue proportion of attention was given to obtaining increased energy densities, whilst mere lip-service was paid to the need for controlling convection losses. Such a line of development was natural and may in the end prove advantageous, since great care will have been taken to ensure efficient control of the radiation.

The design of an efficient radiant heating unit would have presented as many difficulties to the heating engineer as did the problem of an efficient oven to the illuminating engineer. Furthermore, the effects of faulty reflector form would be far more difficult to observe in an otherwise well-designed oven than are the present faults with regard to the control of convection.

Electric Bulbs as Sources of Heat.—The first item to receive attention was the source of radiation for which Groven had used a carbon filament lamp. The carbon filament was shown to be a very efficient radiator, even more efficient than the tungsten lamp. Over its life, however, the carbon lamp was found to give slightly inferior results

owing to the severe blackening of the glass bulb. As a practical source, therefore, the tungsten filament lamp seemed to be the more satisfactory, and at first, lamps similar to the ordinary lighting service bulbs were used. It was decided that economies could be made by running the tungsten filament at a slightly lower temperature for radiant heating purposes than for lighting, since the light output was not important. The filament was therefore run at 2500° K. and this allowed a rated life of up to 10,000 hours.

In these first radiant heating lamps the filament form used was the same as that used in the house lighting bulb, i.e. a crescent-shaped spiral. This state of development was reached much earlier in America than in this country, and as the war has had an adverse effect on further progress here, the newest types of radiant heating lamp are only in use in the U.S.A.

The standard radiant heating lamp in this country is a 250 watt lamp very similar to the ordinary 200 watt house lighting bulb in appearance.

In the U.S.A. it was soon found that this lamp could be improved in two respects. The wattage could be increased, so 500 watts and later 1000 watt lamps were made. The form of filament was not suitable for use with a small reflector if accurate control of the radiation was to be attained, so a more concentrated form of filament was adopted. These developments did not, of course, proceed in isolation and certain modifying factors were introduced. The tendency to build more enclosed furnace leads to the radiant heating lamp being required to stand more severe temperature conditions than its lighting service prototype. The results of submitting the lamps to too severe temperature conditions are: (*a*) failure of the cement which attaches the cap to the glass bulb, and (*b*) melting of the solder on the contact at the base of the cap. While the latter can easily be overcome, the former presents a very serious difficulty since a really satisfactory cement for high temperatures is not available. Two solutions have been attempted, however, viz. (*a*) the use of what are known as Bi-post lamps (Fig. 13) and (*b*) the extension of the cap up the glass shank of the bulb, the latter being gripped mechanically with an asbestos washer.[6]

The Bi-post lamp is the ideal solution; the support for the bulb is the heavy current carrying leads, which are made of a nickel-iron alloy and sealed directly to the glass. This type of construction is not easy to manufacture, especially in the smaller sizes, and it is for this reason that the alternative construction, using an ordinary cap reinforced by an extra collar, has found favour.

The latest stage in the development of the source of radiation is the sealed beam unit. Here the bulb, the reflector, and the front dispersion

lens are combined into one (Fig. 13). The bulb consists of two components, one of which is the reflector and the other the front lens. Both parts are made of a hard glass, the reflecting part being covered with a layer of aluminium (deposited by a vaporising process) or silver;

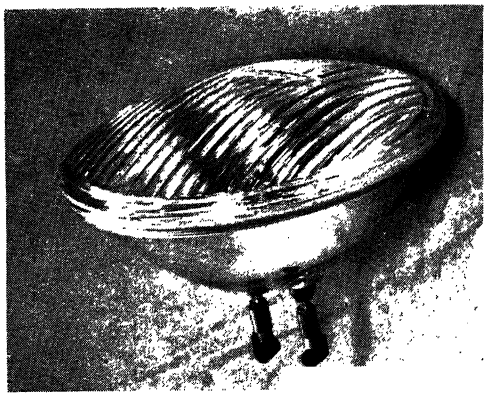
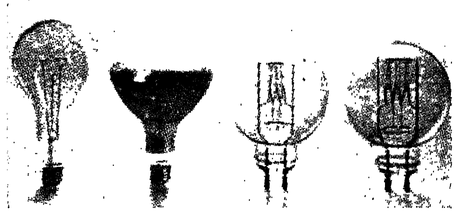


Fig. 13.—"Sealed beam" unit with bi-post fitting

the inside surface of the front lens is shaped to give the radiation distribution required. This unit is made with the Bi-post type of fitting. A unit is also made, which may be looked upon as lying halfway between the ordinary bulb and the complete sealed-beam unit.



(*a*) (*b*) (*c*) (*d*)

Fig. 14.—Radiant Heating Lamps

(*a*) Modified lighting service lamp
(*b*) Lamp with internal silvering
(*c*) Bi-post lamp (500 watt)
(*d*) Bi-post lamp (1,000 watt)

The bulb is of the conventional blown construction, but shaped in the form of a reflector, and the inside is coated with a reflecting surface. The Edison screw type of cap is used and this is reinforced by an additional collar. Some typical modern heating lamps are shown in Fig. 14.

In the early type of bulb the filament shape was, as stated above, the conventional crescent. The unsatisfactory nature of this type of filament was early recognised at the Ford works, and the superiority of

the carbon filament as regards shape was one of the factors favouring the use of this type of bulb. McCloud (7) gives photographs and quotes experimental results which demonstrate the importance of correctly positioning the filament with respect to the reflector. These results are used as an argument in favour of the carbon filament bulb, and on purely opportunist grounds this would appear to be justifiable, but the results can also be used to stress the importance of designing suitable tungsten filaments. From the evidence given by Tiller and Garber it would appear that this development has been made; a compact form of filament is used, and so designed that more of the energy emitted is thrown on to the reflector than by the crescent-shaped arrangement.

The dull-emitter electrical element is another source of radiant energy which may prove of value. A typical unit consists of an electrically heated metal resistance totally encased in cement or enclosed in a metal chamber. Such a unit runs at a lower temperature than the open metal filament and the maximum of the spectral energy distribution occurs at between $2{\cdot}6\mu$ and $7{\cdot}0\mu$.

Such heaters have been in use for some time for therapeutic purposes and are designed so as to emit preferentially those wave-lengths which penetrate deepest into living tissue. By the use of such carefully selected radiation it is found possible to apply larger doses without causing local overheating and discomfort.

Using a dull-emitter unit the heating rates for various coloured finishes would be as shown in Fig. 29, p. 55, for gas as opposed to those shown for the tungsten filament lamp. The use of a reflector would, however, render it open to some criticism, as this would require cleaning.

Development of the Reflector.—The story of the development of the reflector, both as regards its shape and the reflecting material used, is similar to that of the bulb. At first existing shapes were employed and the material was chosen because of its recorded characteristics. The use of large filaments, and the fact that the equipment was at a considerable distance from the work, when used to repair blemishes, led to a preference for shallow parabolic reflectors. As with all projection equipment before the scientific background could be developed, shallow reflectors were followed by deep ones. The first installations were not capable of giving very uniform distributions of energy, and it will be remembered that the Ford Motor Company were first only able to apply the method to the primer coats of automobile bodies. In this country the development is still in the shallow reflector state. The shapes have been worked out with some care, but not in the complicated manner adopted by the Hall Lamp Company (8). In this country one company markets a trough reflector (Fig. 15), and it is claimed that

the more compact spacing of the bulbs allowed by this type of reflector more than compensates for the loss in control caused by the use of a cylindrical section, as opposed to the conventional axially symmetrical reflector. This claim seems rather hard to justify, but in view of the severe limitations imposed by the use of the crescent-shaped filament, the end may justify the means. There is no doubt that the high energy-densities obtainable by this design have produced excellent results, but with the advent of carefully designed bulbs, it is unlikely that this design will have anything to offer over the more conventional form. In

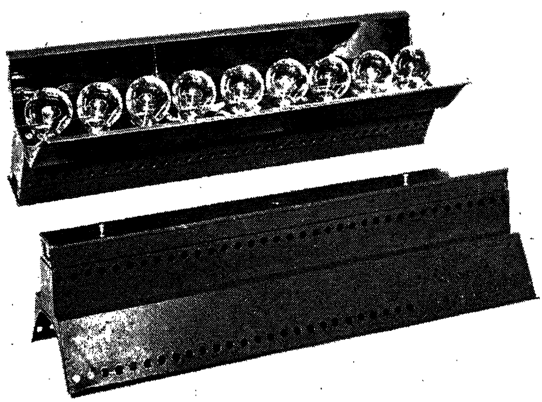


Fig. 15.—Trough type reflector unit
(Courtesy of the General Electric Co., Ltd.)

the U.S.A. the availability of more compact filaments has encouraged not only a better reflector, but also the use of cover glasses to give a more uniform distribution of energy. So far as the authors are aware cover glasses have not, as yet, been used in this country, either for the control of the radiant energy or as a protection for the reflector. The fact that a cover glass will absorb approximately 20 per cent of the incident energy is a very serious reason against its use on the open type of oven. In the enclosed type of oven the heat absorbed by the glass heats the air in the oven by convection, and so the absorption is not so important; further, the protection afforded to the reflectors is also advantageous. Deep reflectors and front lenses have the effect of reducing the working distance between the mouth of the reflector and the work being heated. For a flat bank, a deep reflector can be designed for use with the ordinary crescent-shaped filament to work at six inches from the object being treated, while the ordinary shallow parabolic reflector has a working distance of approximately two feet. Clearly, the use of a shorter working distance leads to a more compact design.

Types of Reflectors.—As a result of careful reflectivity measurements Groven decided that the most suitable materials for the reflecting surface were gold or, later, anodised aluminium. At first the latter was in the development stage and gold-plated reflectors were the only ones which could be considered practicable. A freshly prepared silver surface has a slightly superior reflectivity to gold, but tarnishes far too rapidly

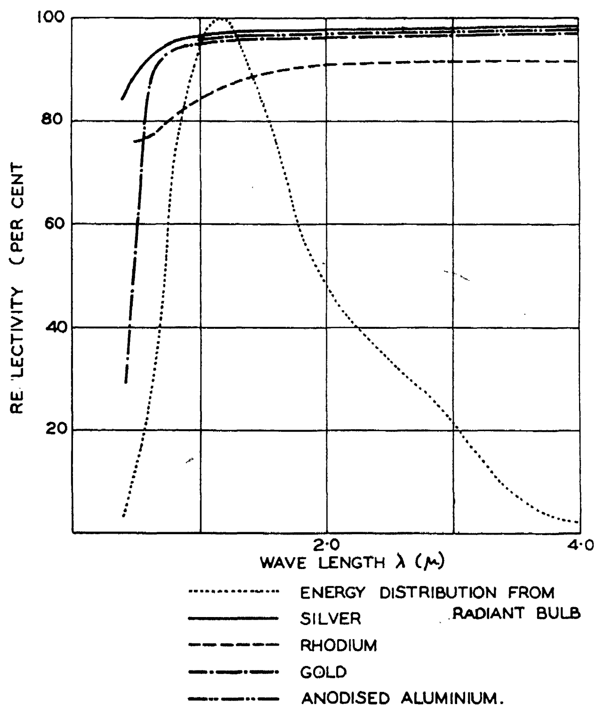


Fig. 16.—Reflectivity of metals in the infra-red spectral region

to be of any use in practice. Protection of the silver surface does not appear to be possible, at least not in a satisfactory manner, since it must be able to stand the removal of injurious deposits, which will be unavoidable unless a front lens can be used. Industrial experience indicated that the gold-plated reflector was not entirely satisfactory, as although it was possible to clean the gold plate, in time the gold surface was worn away. In this country gold has been used in preference to the obviously superior anodised aluminium, because of the restricted supplies of the latter metal. Reference to the curves showing the reflectivity characteristics of various metals will show that in addition to anodised aluminium and gold one other metal could be used, namely, rhodium. Rhodium-plated mirrors have been known for some time,

but their price is high, and as the results are not superior to those obtainable with anodised aluminium, their use has been confined to purely optical fields, where their better surface finish is the controlling factor. In the near infra-red region the reflectivity of rhodium is very high, and so whilst aluminium is in short supply, it should prove more suitable than gold. As can be seen from the curves (Fig. 16), the reflectivity of all these metals in the region of the maximum of the tungsten filament emission is of the order of 90 per cent, so that there is little to choose between them on performance grounds.

The methods of producing various types of reflecting surface will be discussed in the next chapter.

CHAPTER IV

REFLECTORS: MATERIALS AND DESIGN

Reflectors should be accurately made, and are usually either metal pressings or spinnings. Pressings are readily produced in quantity, but elaborate tools are necessary, so that the method is impracticable unless large quantities of a single reflector-shape are required. On the other hand spinnings are individually produced and this method has the advantage of flexibility so that it is possible to make any number of reflectors specifically designed for a particular installation cheaply and quickly. This is a great advantage when experimental and test units are being made up. Pressings are, of course, essential where reflectors of more complicated design are required, or where their form is not amenable to spinning.

Reflector Materials.—The selection of a reflector material must be made on a basis not only of its initial reflecting characteristics but also on account of the durability of its reflecting properties over a long period of service. Thus silver has very high reflective properties but it tarnishes so rapidly in service that it would be of limited value as a reflector in a radiant heating oven. All reflectors (other than those of the "sealed" type described below) will become more or less tarnished and their reflectivity impaired by condensed vapours derived from the varnishes being dried. It is important that these accumulations should be readily cleaned from the reflector surfaces without impairing their efficiency or damaging them unduly, and that moreover tarnishing should only occur relatively slowly. The cleaning of perhaps a thousand reflectors and the removal and replacement of a similar number of lamps is a laborious process, and it is obvious that the less frequently it has to be done the better. The risk of lamp breakage is also considerable and for this reason the construction of the reflectors should be such that it should not be necessary to clean them unduly frequently.

Anodised Aluminium.—On all counts there is little doubt that the best reflector is of the anodised aluminium type. Aluminium reflectors properly anodised have remarkable durability and a very hard-wearing surface. They do not tarnish and are readily cleaned by washing with suitable solvents to remove condensed varnish, and residues. A particularly excellent feature is the fact that their reflectivity is retained at high temperatures; thus according to Pullen a reflector behind a one kilowatt heating element retained 95 per cent of its original reflectivity after 1500 hours of service.

An alternative method of making use of aluminium in reflecting consists in vaporising the metal *in vacuo* and condensing it on to the face of a polished glass reflector form. The aluminium reflecting surface thus produced needs no further treatment. Such reflectors can be fitted with a glass cover plate enclosing the bulb filament completely, as has already been described. They have the disadvantage, however, that the failure of the tungsten filament involves replacing the whole reflector instead of a bulb only. The ordinary aluminium reflector can also be built into a sealed unit.

Aluminium itself takes a good polish, but its reflectivity in the visible range is about 65–75 per cent even when it has received the highest degree of polish that can be given by mechanical methods. On the other hand chemical and electrolytic treatments have been developed which enable the reflectivity to be increased to 80 or 85 per cent in the visible range and even higher in the infra-red spectral region. Mechanically polished aluminium cannot be readily made to give specular reflection because the metal flows under the polishing buff, preventing the development of a truly planar surface.

The Brightening of Aluminium.—In the electrolytic brightening of aluminium the smoothing effect is caused by the preferential attack of the solutions used on the ridges left by the previous buffing process so that the surface is smoothed. The effect has been explained as being due to the formation of a uniform and coherent oxide film on the relatively even surface of the metal whereas any peaks or ridges projecting above the general surface are covered by an imperfect or non-coherent film. Hence the etching process attacks these regions preferentially until a comparatively smooth surface has been produced, when the thin, uniform oxide film proceeds to cover the latter also. This thin oxide film can readily be seen after the brightening process by drying the surface, when it manifests itself in the form of brilliantly irridescent interference colours on the metal.

Immediately following on this brightening treatment the surface is protected by anodising, which produces a hard transparent oxide film over the brightened metal.

Reflector Processes.—The two best-known anodic reflector finishes are those produced by the "Alzak" and the "Bryal" processes, both of which are fundamentally similar, inasmuch as they consist of a preliminary brightening process followed by anodising to protect the brightened surface.

Mason discovered that aluminium could be brightened by making it the anode under suitable conditions in a solution of fluoboric acid,(9) whereby the reflectivity could be raised to 80–85 per cent. In addition to the smoothing effect, the brightening process removes traces of

impurities which are always present in the surface of even the highest quality commercial aluminium. Of these impurities silicon and copper are considered to be the most deleterious. The "Alzak" process makes use of a variety of acid electrolytes, including perchloric, chromic or fluoboric acids with various additions.[10] Subsequently a hard, clear, transparent oxide film is formed on the surface by anodic treatment in sulphuric acid of about 10 per cent strength. The film is finally "sealed" by some such method as immersion in boiling water or cobalt acetate solution; a variety of other substances have been used for the sealing process. In all cases a conversion of the oxide film occurs, and as a result of complex chemical changes its intrinsic porosity is much reduced and the film becomes non-absorbent and relatively impervious. The film thickness is usually of the order of 0·0002 in.

After the brightening process described above, a very faint white surface film is left which has a dispersing effect on the light and makes good specular reflection difficult to secure. This film persists through the subsequent anodising operation, and cannot be removed satisfactorily by any mechanical means either before or after anodising. Whilst this film does not have any serious adverse effect on the total reflectivity of the surface, it is worthy of note that a recently developed process[11] has made it possible to remove the layer by a system of cleavage in the plane of the anodic film. After the brightening operation the aluminium is immersed in distilled water and heated to a temperature of 80° C. for ten minutes. When the metal has cooled again to 20° C. it is immersed in a solution containing:

Sulphuric acid .	7 per cent
Aluminium sulphate	0·1 ,,
Gelatine . .	0·2 ,,

After about a minute the surface film is said to crack and flake off, and the underlying fully bright surface thus exposed can then be anodised in the normal manner.

The "Brytal" Process.—The "Brytal" process[12] differs from the "Alzak" process in that it makes use of an alkaline brightening bath consisting of 3–20 per cent of sodium carbonate, with or without the addition of ammonium phosphate, potassium, or sodium phosphate, etc. The pH of the solution is important, and should not be less than 10. The temperatures used are of the order of 75° C.–85° C. The pH is maintained by the addition of ammonia, or compounds such as hydroxylamine may be used. The aluminium is first immersed without current in order that a certain amount of preliminary pickling may take place; when a uniform rate of attack has been seen to develop, direct

current at a potential of 10–14 volts is applied whilst the parts are still immersed in the same bath to effect anodic brightening. The current density is of the order of 10–15 amps. per sq. ft., the aluminium being the anode. After some 20 seconds the current density falls to about half the above value, and the treatment is continued for ten minutes. The article is finally washed and given a transparent protective oxide film in a sodium bisulphate anodic bath.

The bisulphate solution consists of 25 per cent by weight of sodium bisulphate dissolved in water with or without special additions, such as sulphuric acid, boric acid, or phosphoric acid; 6 to 12 volts are needed, and the current density is of the order of 5 amps. per sq. ft. (preferably D.C.).

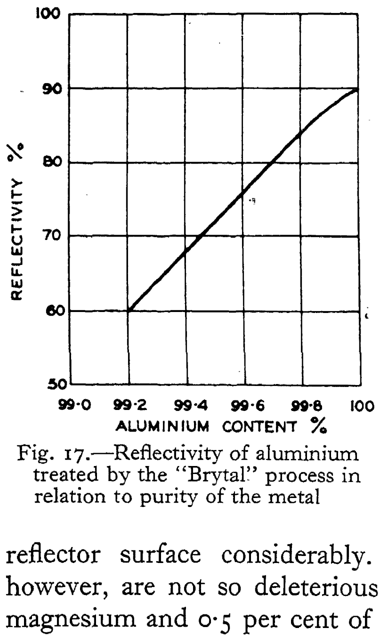


Fig. 17.—Reflectivity of aluminium treated by the "Brytal" process in relation to purity of the metal

In both of these processes the anodic film itself is hard, glossy, and highly transparent, and serves simply to protect the bright metal surface. It does not detract from the original reflectivity of the brightened aluminium, and in some cases may even increase it.

For the best results the aluminium should be of high purity; copper and silicon, when present in any quantity, impair the efficiency of the reflector surface considerably. Magnesium, manganese, and zinc, however, are not so deleterious. An alloy containing 0·5 per cent of magnesium and 0·5 per cent of silicon has been developed in America for use for reflectors, as have also less pure aluminium alloys coated with high-purity aluminium.([13]) The reflectivity increases linearly from 99·2–99·8 per cent purity of the aluminium after which it increases less rapidly (Fig. 17).

Anodic films can be dyed a variety of colours before the "sealing" operation by immersion in boiling solutions of suitable dyestuffs, but there is little advantage to be gained by colouring the reflectors in this way.

Anodically brightened reflectors are said to show a marked absorption bend for radiant heat of wave-length 3μ;([14]) this is due to an adsorbed film of moisture on the surface which can be reduced by suitable after-treatment of the anodic film.

Gold-plated Reflectors.—Gold has extremely good reflecting qualities in the infra-red region, and it does not readily tarnish. To be of

maximum service gold-plated reflectors must, however, have an adequate deposit of the precious metal, and due note should be taken of the characteristics of gold deposits.

Gold-plated reflectors may be made on a base of steel, brass, copper, etc., but in any case it is important to note that the gold will not protect the underlying metal from tarnish or corrosion unless it is of adequate thickness and the base metal is not exposed. Should the gold coating be penetrated rapid deterioration of the exposed area will take place. Gold deposits are very close-grained and are not subject to porosity to any extent when they are plated from the double cyanide solution, as is usual nowadays. This consists of a solution containing the alkali gold cyanide, either $KAu(CN)_2$ or $NaAu(CN)_2$, which gives a better rate of deposition than does the older chloride bath containing auric chloride ($HAuCl_4$) and an excess of acid or soluble alkali chloride. The solution has also a substantially better "throwing power."

The precise colour of the gold plate can be varied at will by modifying the bath composition, its temperature, or the current density at which plating is carried out. In all cases the deposits are pure gold, the difference being due to their physical structure and the nature of the underlying metal. Thus the colour is made more pale or yellow by increasing the free cyanide content of the plating solution or by lowering the current density. A deposit over silver or nickel will have a light yellow colour, and on copper a more reddish colour than on brass, whilst the composition of the brass may affect the colour of the gold deposited on it.([15]) Gold alloys can also be plated and gold-copper and gold-silver alloy deposits have been used, although even those seldom contain less than 92 to 96 per cent gold.

When reflectors are made of brass the thin gold film is liable to diffuse into the latter metal, especially under the high temperature conditions prevailing at the surface of the reflector. For this reason it is desirable, if not essential, to plate the brass with a deposit such as nickel, which is then highly polished immediately before the gold is applied. The nickel deposit should be of the order of 0·0005 to 0·0010 in. thick to allow for buffing. In the case of steel reflectors the greater thickness of nickel is to be aimed at because of the nature of the base metal which cannot be given so high a finish as brass; thus more polishing of the nickel plate is likely to be needed and a greater proportion of the deposit will tend to be polished off. The nickel deposit on steel should be direct, without an intermediate copper coat and electrolytic etching in sulphuric acid is desirable in order to obtain good adhesion of the nickel. The constant heating and cooling of the reflector surface will induce high stresses in the deposited coating so that good adhesion is essential.

The thickness of the gold deposit is less important from the reflectivity point of view than from the aspect of durability. A deposit of 0·00001 in. to 0·00002 in. in thickness would be considered as a reasonable coating for a radiant heat reflector, corresponding to 0·293 to 0·586 dwt. per sq. ft. of the reflector surface. Greater thicknesses of gold can, of course, be readily applied with a corresponding increase in the effective life of the reflector.

The gold-plated reflector is finally polished with a soft mop, making use of fine rouge, when a highly reflecting surface is obtained.

It is common practice to lacquer gold-plated articles, but this must not be done where reflectors to be used for radiant heating are concerned.

Silver-plated Reflectors.—Silver surfaces are capable of taking a very high finish and give excellent reflection, both in the visible and infra-red ranges. Silver-plated brass (electro-plated with 0·00001 to 0·00005 in. of silver) is commonly used for lamp reflectors, especially in motor-car headlamps. Silver has the disadvantage, however, of extreme liability to tarnishing, so that the initially high reflectivity is not maintained for long in the open type of reflector unit. In the manufacture of motor-car headlamps the silver surface is generally spray-coated with a special heat-resisting lacquer. The difficulty of cleaning a lacquered surface makes the use of this type of reflector impracticable in a radiant heating plant.

Rhodium Plating.—Silver plate can, however, be used as a basis for rhodium-plating, although a nickel undercoat is to be preferred for reflectors.

Rhodium is a precious metal, and is costly. A rhodium surface is, however, very hard, completely non-tarnishing, and has high reflectivity characteristics. It is therefore well adapted for use as a reflecting surface in radiant heating ovens.

Rhodium can be plated on to silver, nickel, nickel-silver, copper, brass, or gold. On the other hand, metals and alloys such as iron, aluminium, or solder, cannot be directly plated with rhodium, and in these cases a deposit of silver is generally applied as an undercoat. Rhodium deposits are extremely thin, usually about 0·000005 in. in thickness. In the case of reflectors, these should preferably be made from brass, highly polished, and then nickel-plated prior to rhodium-plating. Steel can also be used, but brass is to be preferred. The finish of the basis metal is important as the rhodium-plate precisely duplicates the appearance of the underlying surface. Thus, water stains on the surface or finger-marks caused by careless handling will show themselves on the finished rhodium-plated reflector.

On emerging from the plating solution the rhodium surface is fully bright when the finishing of the underlying metal has been satisfactorily

carried out. Sometimes, however, there may be local areas of "milkiness," particularly near edges or projections. These can usually be removed by polishing with a mop, using magnesia as the polishing medium. Rouge is unsatisfactory, as it accumulates in the pores of the metal surface and impairs the appearance of the reflector.

Chromium Plate.—Chromium-plated reflectors are cheaply and easily made. The chromium should be plated on to a nickel deposit applied directly to the brass or steel. A suitable thickness of nickel would be of the order of 0·0003 to 0·0005 in. on brass, and 0·0005 to 0·0007 in. on steel. The nickel provides the protection against corrosion for the underlying metal; the thin chromium deposit only serves as an anti-tarnishing coating for the nickel. Direct chromium deposits on brass being highly porous and discontinuous are unsatisfactory. The chromium coating does not generally exceed 0·00001 to 0·00002 in. in thickness. Chromium is usually bright as deposited, but any areas of milky appearance in the plate can be polished by means of chromium oxide polishing compositions. The reflector surface is hard and durable, but although the reflectivity is good in the blue and near ultra-violet spectral regions, the reflectivity for visible and infra-red radiation is not so good. Chromium-plated reflectors are therefore little used for infra-red work when better reflector materials are available.

Cleaning of Reflectors.—The removal of hardened lacquers and the cleaning of reflectors sometimes presents a problem owing to the high tenacity of the material deposited on the metal surface. One of the most satisfactory solvents for polymerised and oxidised oils is undoubtedly methylene chloride, and there are a good many proprietary paint removers based on this solvent on the market. Methylene chloride itself is a pale yellow liquid, with a pleasant odour; it is highly volatile, and has the advantage of non-inflammability. Another very useful ingredient of paint removers of this description is normal butyl acetate; other media, such as carbon tetrachloride, are sometimes included. In practice it is often found that ordinary cellulose solvents or thinners will remove the condensation from the reflector surfaces quite satisfactorily, and such cleaning need not be carried out more frequently than about once in every six weeks. The reflectors are finally wiped with a non-abrasive polishing composition applied on a cloth. Emulsified preparations on a paraffin and water base with a small soap and wetting agent content are especially suitable for the final polish after cleaning. Anodised aluminium and, to a lesser extent, rhodium-plated reflectors will withstand a certain amount of abrasion; gold-plated surfaces, on the other hand, are extremely soft and must be cleaned with great care to prevent damage. In the case of the latter the gold plate will in time wear off with constant cleaning. The reflectors can

then be readily replated. Anodised reflectors can also be re-finished, the procedure being to strip the anodic film off chemically, re-polishing and re-anodising as already described.

Rhodium plate cannot be stripped off the base metal; the best procedure in the case of worn or damaged rhodium reflectors is to silver-plate over the old rhodium, polish the silver, and then apply a further rhodium deposit over the latter.

Reflector Design.—The history of radiant heating lamp units begins with the simple parabolic reflector designed to give an efficient projection at a relative great distance and reaches its present state of

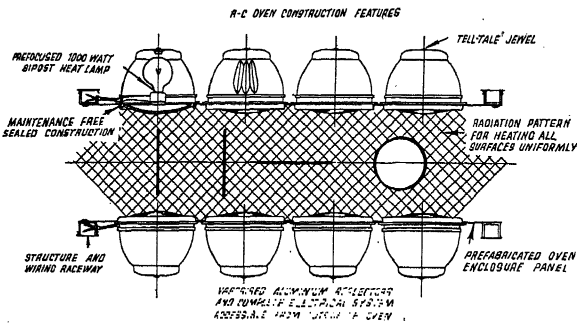


Fig. 18.—Diagram illustrating modern radiant heating oven design (Cusack)

development in a unit complete with dioptric glass to give a smooth energy distribution and a shorter working distance. The principle advantage of the long working distance is the flexibility it allows. When a relatively uniform distribution of radiation has been achieved at, say, 2 ft. from the unit, it does not matter whether the work is 1 ft. 9 in. or 2 ft. 3 in. away. When a unit is designed for closer working the simple types of design will lead to a much more critical performance.

This critical requirement of the working distance is of no consequence if only one simple shape of component is to be stoved in the installation, but designers must envisage a universal type of oven in which a wide tolerance on the working distance is a prime requisite. The complex type of reflector used by the Hall Lamp Co.,[16] is one method of solving the critical nature of the simple-shaped unit fitted with a plane glass (Fig. 18). Such units require much thought in design and depend upon the use of accurately made filaments for their function. Furthermore, special types of bulbs must be available in order that they may be of maximum value. These conditions prevail in the U.S.A., but not in this country, and so an alternative solution has to be attempted. A recently developed experimental unit is illustrated in Fig. 19. This unit is intended for use with the conventional crescent-shaped filament

and gives a working distance of 6 in. Two methods are available for obtaining the required flexibility; one being the use of an etched bulb surface, which is common on the radiant heating lamps supplied in this country, and, secondly, by the provision of suitable focusing arrangements so that the relative position of reflector and bulb can be altered to suit the working distance. A hard glass cover is used to protect the reflectors from injurious deposits, so that they will not have

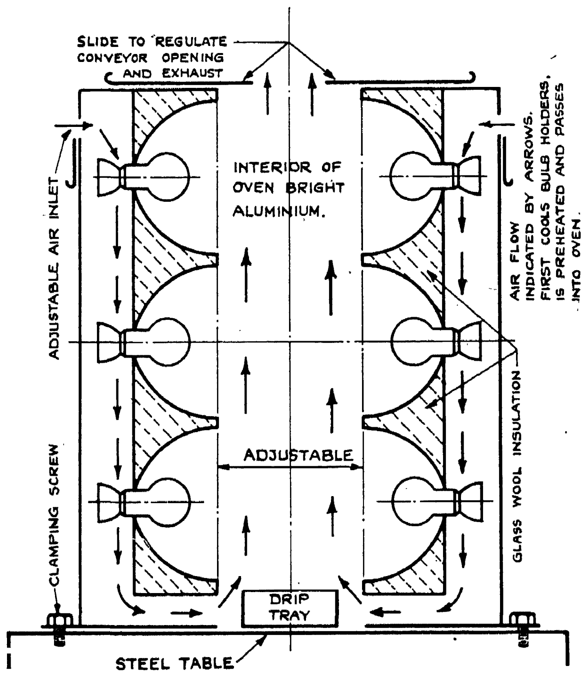


Fig. 19.—Diagram of experimental radiant heating oven (Courtesy of Joseph Lucas, Ltd.)

to be cleaned so often. A still more effective method is to mount the bulb independently of the reflector, and so that the reflector itself can be removed for cleaning without disturbing the bulb. Such an arrangement of reflector and bulb is not possible with the present type of radiant heating lamp.

The solution to most of these practical difficulties lies in the use of the sealed-beam type of unit. The distribution of the energy can be correctly effected without the losses caused by an external reflector and front glass. Only one surface remains to be kept clean, and, finally, suitable design should enable very much higher energy densities to be available than with any other arrangement.

CHAPTER V

PLANT CONSTRUCTION AND DESIGN

Reference has already been made to the radiant heating plants at the Ford Works, where the industrial use of the process was first developed on a practical scale. It has been stated that the essential features of modern installations are very similar to the original "blemish repair" unit. While this is so as regards the open nature of most installations, this does not mean that the experience of the last ten years has taught designers nothing. As has been explained, much detailed attention has been paid to the design of radiant heating lamps and reflector units, and this work has enabled equipment manufacturers in this country to market standard sections from which almost any required installation can be built up.

A typical illustration of a present-day plant is seen in Fig. 20. This is a universal stove with lines of reflector units so mounted that a wide variety of tunnel shapes can be achieved. As this is a laboratory tool, the control of the air-flow has to be attained by the use of suitable canvas sheeting. In a recent publication on the application of radiant heating, Maxted(22) stresses the importance of controlling the air-flow in production plants, though perhaps not to the same extent as the present authors.

Many production plants have initially been built without due regard to the control of convection with the result that much power has been wasted. Subsequently some attempt was made to control the air-flow by the use of canvas sheets hung at the sides of the plant. Such expedients, while providing crude control, are by no means a suitable substitute for a carefully designed oven. These plants work, and in many cases fully justify the expense of running them, because, in spite of a relatively low thermal efficiency, they are capable of drying finishes at a rate hitherto unprecedented. The gain to be expected by a more careful approach to convection problems would mainly be confined to a very substantial reduction in power costs. In addition, slight increases in speed are to be expected owing to the fact that even higher heating-up rates will be attainable in a controlled-convection radiant heating oven.

A more enclosed installation than those previously mentioned has recently been constructed. This plant is designed with automatic spraying arrangements so that two coats of lacquer can be applied to the insides and two coats of paint to the outsides of hollow sheet-metal pressings. The components are put on the conveyor at one point,

sprayed and stoved, then immediately on leaving the oven sprayed again and stoved a second time. The first two lacquer coats have six minutes stoving each. The components are then cooled rapidly with a blast of air and reversed by hand, after which the two coats of paint are applied. Each coat has two minutes' stoving. Finally, the components cool down while they complete the circuit of the conveyor and are removed just before the loading-point.

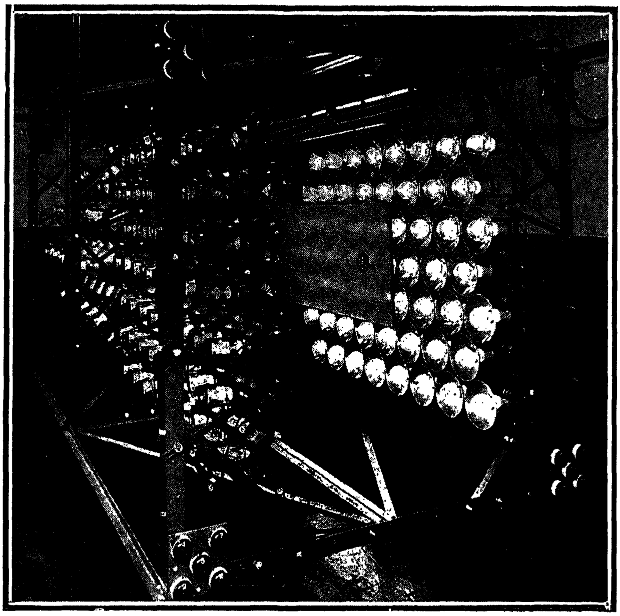


Fig. 20.—Experimental radiant heating Equipment (Courtesy of the British Thomson-Houston Co., Ltd.)

The arrangements of the reflectors in these ovens has been carefully designed for use with the components in question, and each oven is completely enclosed in a sheet-metal casing and fitted with special exhaust heads to remove the fumes from the shop. This type of plant represents a very considerable advance over the open-frame type of unit.

In the U.S.A. the position as regards the design of ovens and their component parts is considerably in advance of this country. The open type of unit is still referred to and a variety of applications—many of an emergency nature—illustrated. The General Electric show the use of a more enclosed type of pre-fabricated unit,([17]) while the equipment described by Cusack([18]) shows that the designs of the Hall Lamp Co. are in a very advanced state of development. Full advantage is taken of the heat content of the air in the oven. This is circulated and used for pre-heating the incoming parts. The whole of the interior of the

oven is made reflecting so that as much as possible of the radiation is re-directed on to the articles to be heated. The lamps are designed to give an even field of radiation throughout the oven, so that all surfaces of the articles are subjected to approximately the same energy density. A typical oven of this type is shown in Fig. 21.

The undoubted success of even the crudest open type of oven must not be allowed to lead to the notion that these later developments are only of secondary importance. The saving in power consumed will

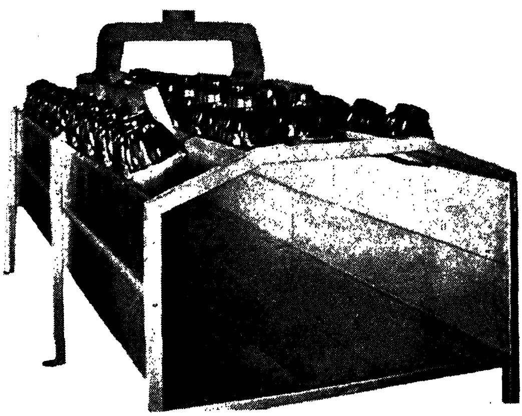


Fig. 21.—A recent radiant heating sub-assembly (Cusack)

not be the only result; there will be even further reductions in heating-up time so that more applications will become economic. Plants will be more compact and much neater in appearance. The proper control of fumes will lead to healthier conditions, and, finally, the plant may even in some cases be suspended from the ceiling, allowing the floor space beneath it to be free.

Principles of Oven Design.—Although much progress has been made in the design of lamp and reflector units for radiant heating, the oven design aspect is, as has already been hinted, still largely in its infancy. The tendency has been to suspend the reflectors from a metal framework, little or no provision being made to retain heat or prevent its being dissipated in unwanted directions. It is highly desirable that the air temperature within the oven should be as high as possible, and this can be achieved by constructing the latter in such a way that adequate provision is made for insulation. Tiller and Garber(3) point out that the maximum utilisation of electrical energy is obtained when the air temperature is higher than that of the parts being heated; not

only are higher efficiencies obtained with high air temperature, but also higher rates of temperature rise. In starting up an oven the lamps deliver their optimum energy output almost instantly, but the air temperature will take a considerable time to attain equilibrium; to obtain a uniform product it is therefore desirable to pass the work through the drier more slowly when the plant is first started up.

Exhaust Equipment.—An exhaust must be provided to take off the fumes and vapours resulting from the drying of the paint, but the quantity of air removed in this way must be retained at a minimum. Some type of damper or controlled forced air circulation is therefore desirable if the maximum efficiency is to be obtained. Moreover, the higher the temperature of the air the greater will be the total proportion of radiant heat which is retained by the components being heated. There are always internal temperature losses due to the energy not being entirely concentrated on to the articles being dried. Such losses may suffice to raise the air temperature within the oven to the desired level, but should this not be possible some authorities even suggest the introduction of auxiliary heaters of some kind to increase the oven temperature. This is, however, not likely to be necessary unless the utilisation of the radiant energy is exceptionally high.

Up to the present time it is to be regretted that an undue proportion of the attention of the designers of infra-red drying equipment has been focused on lamp spacing and arrangement. The question of oven design and the maintenance of air temperature within the oven itself has received relatively little attention. Many large plants consist simply of banks of lamps and the air temperature within the "oven" is little more than that prevailing in the room in which the plant is situated.

Whilst it was at one time thought that the bulk of the energy produced by the lamps was transferred directly to the components being stoved, it is now realised that large energy losses result unless undue loss by convection is prevented. Moreover, by raising the air temperature considerable economies both in running costs, and possibly, in the initial outlay on the plant, can be effected as has already been pointed out. Thus with proper oven design a smaller plant can be made to do the work of a much larger unit.

Need for Enclosed Ovens.—In order to make good use of the energy, the oven proper should be carefully enclosed and provision made for controlling draught through it. Leaks and poor joints must be avoided. It is usual to build plants in sections on wheels; these can then be readily removed for purpose of bulb changing, reflector cleaning, and general adjustments. The sections must be made to fit together closely, and it is desirable that some form of heat insulation be enclosed between the reflector backs and the oven walls. The flow of air results

in a temperature gradient over the surface of large articles which has to be corrected by a suitable distribution of the incident radiant energy.

The whole of the interior of the oven not covered by lamp units should be lined with reflecting material to prevent absorption of the radiation and minimise heat absorption by the oven unit itself.

One problem in the design of reflecting units is the question of heat transmission to the backs of the lamps. Some form of air circulation around the bulb-holders is therefore useful to prevent the deterioration of bulb cements and holder units due to the high temperature produced.

Gas-heated Equipment.—Heating by radiation has been extensively used in industry with both gas and electricity as the heating media, but so far as paint-baking is concerned, recent developments have been chiefly carried out by the electrical industry making use of tungsten filament bulbs as the source of radiation. Alternative fuels have not, in consequence, received the attention they deserve. From practical aspects gas is the chief fuel worthy of consideration, and on the face of it the use of gas for this purpose appears to present a number of advantages. As a general rule gas provides a much cheaper source of energy than does electricity. Moreover, the initial cost of a gas installation will tend to be less than that of an electrical plant, as the high cost of switch-gear, transformers, electric bulbs, etc., is avoided. Gas equipment is also in many respects more robust and less liable to deterioration and breakage. As against this, there is the disadvantage that a proportion of the heat produced by a gas plant is lost in the products of combustion which must be carried away. This can to some extent be reduced, however, by using this waste heat for the pre-heating of the air employed in combustion. The presence of a flame may be cited as a disadvantage in the drying of paints, owing to the fire hazard, but similar considerations apply to electrical plants in the event of arcing or lamp breakage. Generally speaking, however, in the drying of the synthetic enamels the fire hazard is not very great.

Recent Developments.—Some interesting advances have been made recently in gas-operated plants in which most of the possible disadvantages attached to the use of gas have been substantially overcome by careful attention to design, so that full use is made of the potentialities of this fuel.

As has already been pointed out, the baking of enamels, particularly those of the synthetic type, is brought about by a polymerisation process which takes place at a temperature usually of the order of 250–350° F. For the most rapid baking it is therefore important to bring the temperature up as quickly as possible, and it is here that the advantages of heating by radiation become evident. Experiments have

been referred to which show that neither the method of heating nor the nature of the source of radiation are relevant; only the temperature-time cycle is of consequence in obtaining efficient paint-baking. These experiments have been extended further in recent work which has shown that the nature of the temperature-time relation is substantially independent of the mode of heating, providing the ultimate temperature is the same in each case. The similarity is found to be an identity in the early stages of heating and only small differences occur as the maximum temperature is approached. In practice only the initial part of the temperature-time curve is used and the practical maximum temperature is much lower than the ultimate temperature which the article would reach if left in the oven indefinitely.

Convection Ovens.—It follows from this that improved drying rates could be obtained by increasing the temperatures used in convection ovens. The design of many such ovens, however, does not lend itself to this, and the introduction of additional gas-burners might result in local overheating whilst the uniformity of the air temperature would almost certainly be poor. In the case of the air-circulated conveyor type of oven with the combustion chamber underneath, it should, however, be quite practicable to increase the oven temperature considerably, thereby obtaining the dual advantage of low convection losses from the articles being heated (due to the high air temperature) and good radiation from the walls of the oven, especially when the latter are well lagged.

The general arrangement of a typical oven of this kind is shown in Fig. 22, whilst the appearance and mode of operation of the plant can be seen from Fig. 23. With this form of oven, which may be constructed either as a direct or indirect fired unit, very uniform temperature conditions can be obtained. Essentially the heating section consists of an insulating casing through which the conveyor passes. The design has been evolved to make the oven self-sealing, so that heat losses can be reduced to a minimum at the loading and unloading ends, which adds to the thermal efficiency of the plant and to the comfort of the operators.

The type of stove shown is of the direct gas-fired air-circulated type, and has proved in practice to be an efficient unit for the stoving of painted, varnished, or lacquered parts of all sizes and shapes.

The design incorporates recirculation whereby the oven atmosphere is returned through the combustion chamber where any inflammable solvents present are burned off and recirculated back through the supply fan and supply ducting into the working space. The supply ducting can be so designed that the optimum air-flow conditions can be attained throughout the working space, and with a properly designed duct

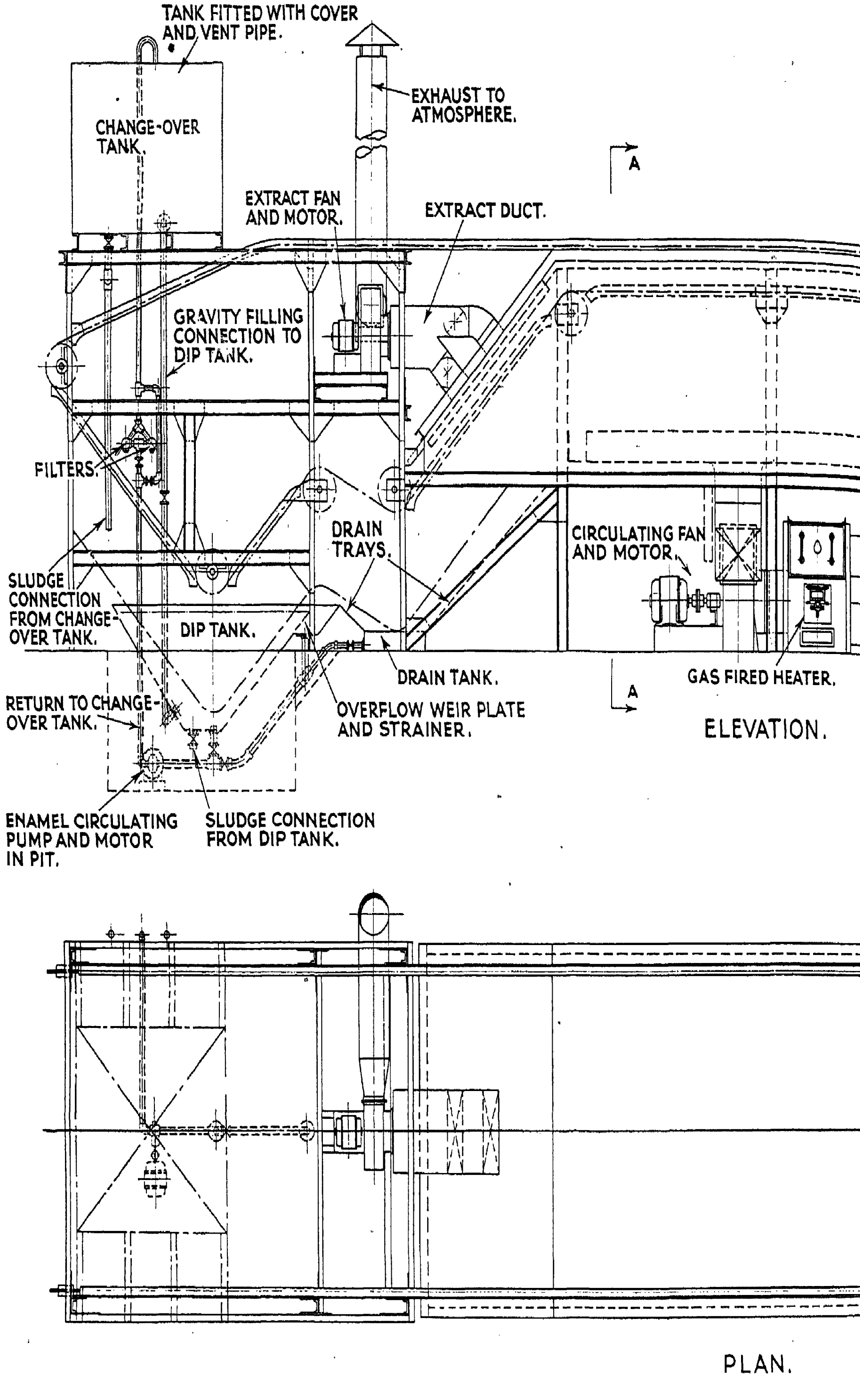
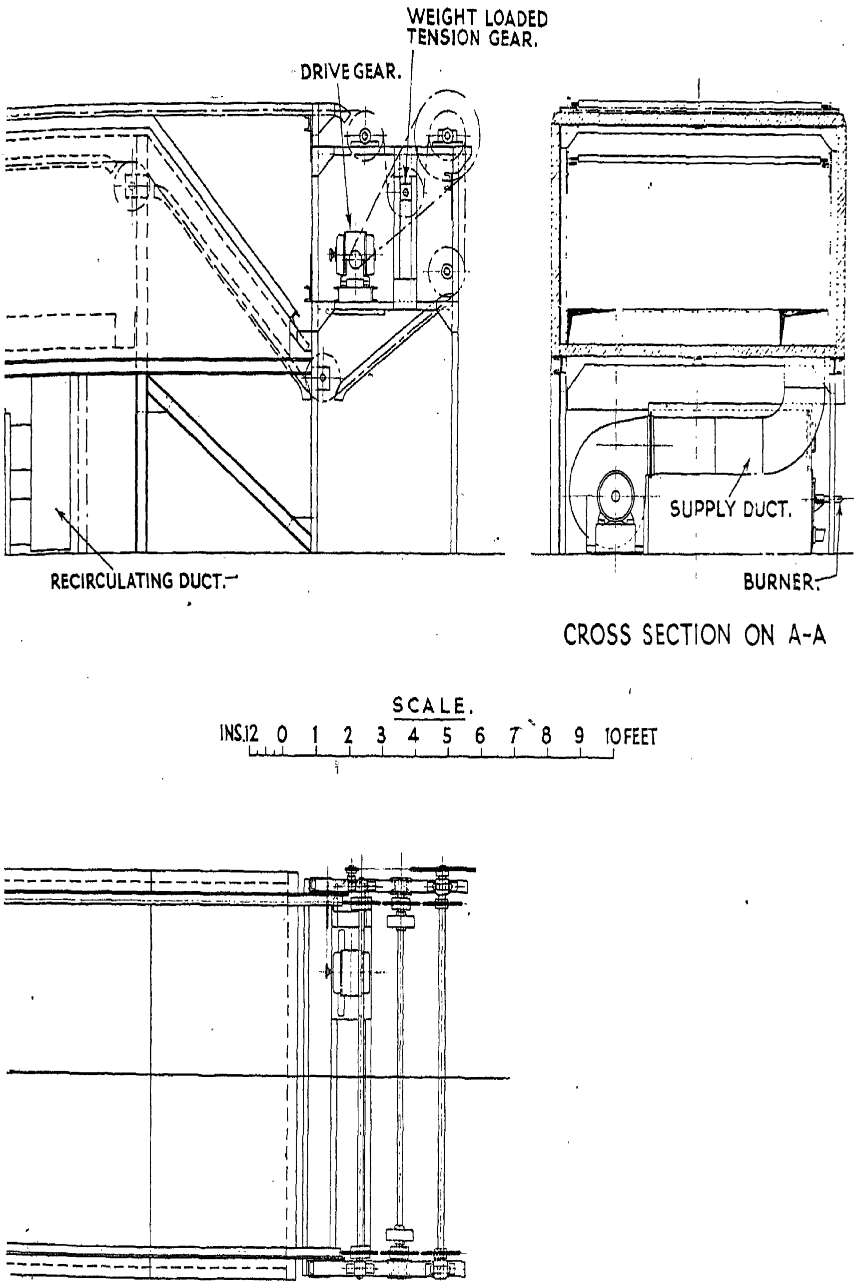


Fig. 22.—General arrangement of conveyorised connection oven



(hump-back type). (Courtesy of Controlled Heat and Air, Ltd.)

system, and utilising the mechanical property of high-velocity air streams to create turbulence inside the working space, very close temperature conditions result, and it is possible to ensure that the articles to be dried are at the desired temperature for the maximum possible time.

With this form of stove an extractor system is generally provided at the loading end in order to remove the fumes which will develop during

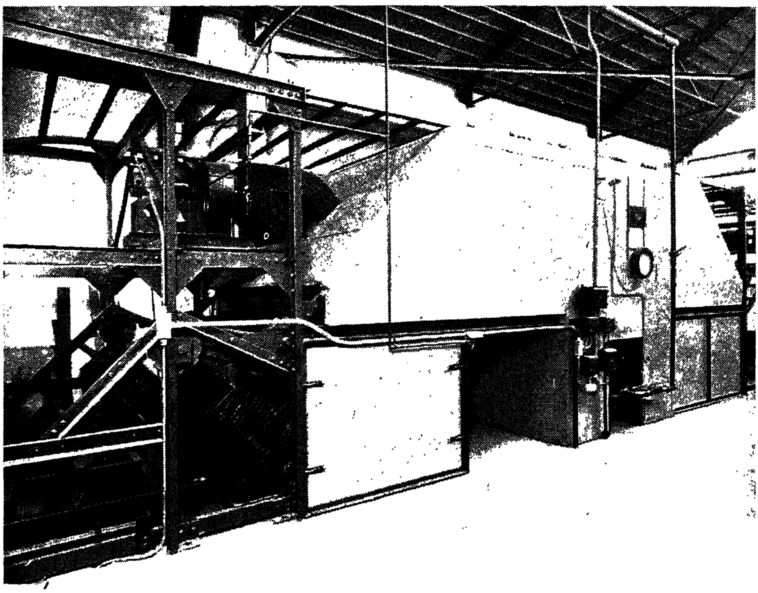


Fig. 23.—Conveyorised convection oven in operation
(Courtesy of Controlled Heat and Air, Ltd.)

the heating-up of the parts to drying temperature, and also to induce at the loading end slight air infiltration in order to complete the seal and avoid loss of heat. This creates convection from the unloading end of the oven, and also ensures that this end, too, is sealed.

When it is desired to ensure that the products of combustion should not enter into the circulating atmosphere a heat interchanger is provided in place of the direct gas-fired air heater shown in Fig. 22. The heat interchanger generally comprises separate gas- and air-spaces, the heating gases passing in the opposite direction to the air-flow to ensure the maximum heat interchange. With this form of heater it is necessary to maintain a fairly high velocity through the tube in order to increase the interchanger efficiency.

This form of stove can be used with all types of fuel, and can be designed so that different working temperatures are easily obtained by

a simple adjustment of a thermostat. Owing to the rapid circulation and to the extractor system, it is impossible for a concentration of volatiles to occur; in this respect the system is superior to the double- and treble-cased stoves.

The heating is primarily by means of forced convection, although it will be appreciated that a part of the drying process will occur due to radiation through the oven walls during the temperature rise period.

On the other hand, the best use could not be made of such radiation in existing ovens, owing to the fact that in ovens designed purely for convection heating no attention will have been given to the "shading" effect on each other of parts passing through the plant. This will prevent the optimum amount of radiation from reaching the surfaces to be baked. The importance of this shading effect is perhaps rather exaggerated by some authorities where thin metal parts of good heat conducting qualities are being treated, but it must nevertheless receive due consideration.

For these reasons present-day convection ovens would not be expected to give the best results obtainable with gas heating. The best procedure is probably to aim both at a higher air temperature inside the oven to prevent convection losses and simultaneously to design the oven in such a way as to make effective use of the direct radiation from the walls; this means a radical departure from general present-day gas-oven practice and, for maximum efficiency, a special plant for each class of article being dealt with. Heating must be arranged so that a uniform wall temperature is obtained, and the wall curvature adjusted so as to maintain as nearly as possible a uniform radiant energy density in the oven itself. These principles are by no means new to the gas industry, and have been made use of to some extent in the treble-cased oven in which the products of combustion are completely excluded from the oven, but are allowed to circulate between the oven proper and the lagged walls.

The Treble-cased Stove.—The treble-cased stove was originally designed for applications where it was assumed, but not always verified, that the products of combustion would cause deterioration to the work to be processed. The appearance of the stove can be seen in Fig. 24, and the design of the heating arrangement is clearly shown in the appended diagram (Fig. 25). Essentially the construction comprises an insulated casing, and generally the burner gear is placed at the bottom of the casing. Inside the insulated casing is arranged a further mild steel casing, the floor of which is suitably stiffened to carry the load and gas spaces are arranged round both sides and at the top between the insulated casing

and the inner mild steel casing. Ventilating stacks are taken through the roof, one connecting to the gas space and one to the working space.

Provision is made in the case of the combustion chamber formed underneath the floor of the working space to admit the necessary air

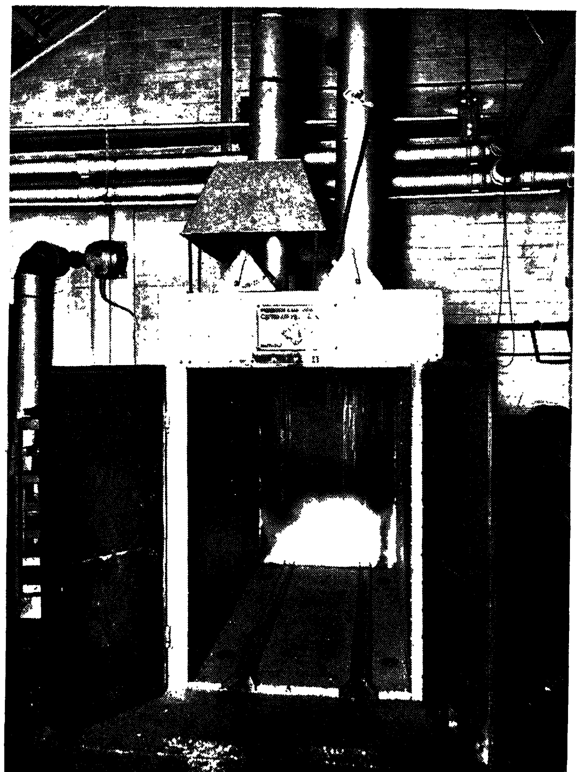


Fig. 24.—Treble cased oven (with door open)
(Courtesy of Controlled Heat and Air, Ltd.)

for combustion, and also for venting the products of combustion. Similar fresh air openings are provided into the working space in order to obtain a degree of natural convection.

It will be realised that with this form of stove, a proportion of the drying process is achieved by natural convection. In the main, the heating is by radiation, and a major trouble which has occurred in this type of stove is that the temperature must vary from the side to the centre of the stove, and also from the top to the bottom. A further difficulty which has been experienced with treble-cased stoves is that designers have made insufficient allowance for venting where heavily

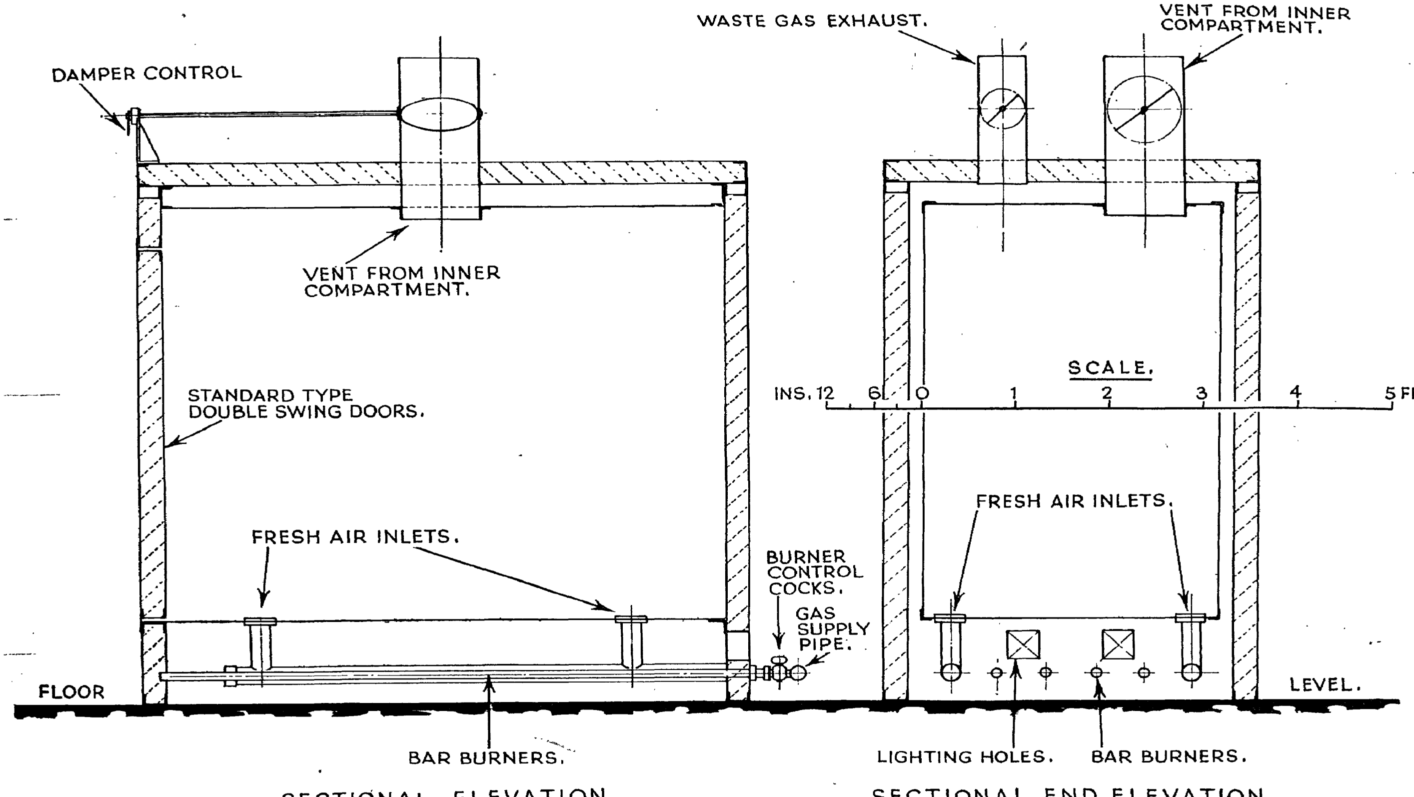


Fig. 25.—Treble-cased oven (general arrangement). (Courtesy of Controlled Heat and Air, Ltd.)

fuming coatings have to be dried and, in consequence, "blooming" and "washing" of the painted articles has resulted.

In running cost it will be appreciated that the treble-cased stove is a comparatively inefficient unit, since, in the first place, the inner casing acts as an interchanger, and consequently the amount of air which has to be taken into the inner compartment for venting has, of course, to be heated to the oven temperature and is immediately discharged to atmosphere after once passing through the working space.

In processes where close control of temperature is required, generally speaking, it is extremely difficult to obtain these conditions in this form of stove.

This type of oven is, moreover, designed for batch operation.

Also studies of the radiation from gas-heated panels and radiant elements have been made in great detail and published by a number of authorities. This work has been especially associated with the development of domestic space heating appliances; whereas the balance between radiation and convection in the latter application differs from that concerned in paint-baking, the fundamentals of the subject are, however, the same in both cases and the results of these investigations can be used with advantage.

Radiation in Convection Ovens.—Even in convection ovens a substantial proportion of the heat transfer may take place by radiation. Thus Andrew and Chamberlain* have determined the heat transferred to a metal sheet suspended in a convection oven in such a way that it is under direct radiation from the walls, i.e. not shielded by another sheet. The figures quoted in Table IV indicate the relative influence of radiation and convection on heat transfer.

TABLE IV

HEAT TRANSFER IN CONVECTION OVENS. RELATIVE INFLUENCE OF RADIATION AND CONVECTION ON HEAT TRANSFER FOR A PLATE BEING HEATED FROM 60° TO 220°F.

Type of Oven.	Method of heat transfer.	Oven Temperature °F.				
		250	300	400	500	600
Natural convection	Radiation %	64·5	65·3	68·2	72·2	76·0
	Convection %	35·5	34·7	31·8	27·8	24·0
Forced convection (5 ft. per sec.)	Radiation %	47·7	48·1	49·0	52·0	57·4
	Convection %	52·3	51·9	51·0	48·0	42·6

* Paper presented to the Institute of Fuel. July 21st, 1943.

The importance of the proportion of heat transferred by direct radiation from the oven walls is therefore evident, especially in the case of the natural draught oven. The purpose and advantages of forced convection ovens, in which the air is circulated by means of a fan installation can also be seen from these figures. A high rate of air-flow serves to break up the stagnant air film which always exists in proximity to the surface of articles being heated; this film is highly insulating and slows up the rate of heat transference from the hot air to the metal very substantially. When the heat is transferred by radiation this air film is without influence on the rate at which the metal receives heat. Its presence may actually be advantageous, since it will reduce the heat lost by convection from the metal which is being stoved. Air movement in any unit in which the main method of heat transfer is by radiation is thus likely to be disadvantageous; on the other hand, when any considerable proportion of the heat is transferred to the work by convection forced air circulation is extremely useful.

The proportion of heat which is transferred by radiation from the walls in the convection oven cannot be unduly increased for a further reason. In the majority of plants it is evident that a substantial proportion of the work being stoved in such a plant will always be shielded from direct radiation and will be heated mainly by the much slower process of convection. Hence those parts which are in sight of the walls of the oven will receive an excessive input of heat so that the enamel may become overheated and discoloured or even burnt. The drying of paints thus exposed to wall radiation generally takes place three to four times as quickly as when the specimens are shielded from direct radiation of this kind.

Uniformity of Heating.—Whether heat transference is mainly by convection or by radiation it is evidently desirable that conditions be as uniform as possible; the overheating of parts subject to direct radiation in a convection oven is manifestly to be avoided. For this reason it is impracticable to exceed temperatures of about 400° F. in such ovens, since if this is done a proportion of the articles being stoved will probably be damaged. Uniform conditions are also promoted by use of forced air convection. Heat losses are minimised by such devices as the humpback oven design which reduces convection losses through the openings of conveyorised convection tunnels.

It is thus seen that if it were possible to design a gas-heated oven in such a way that all the work passing through it were more or less uniformly subjected to heating by radiation from the oven walls, the speed at which enamelled metal parts could be stoved would be immensely accelerated. This has been achieved by means of high temperature radiant panels whilst medium temperature radiant

heating tunnels have also been designed on the lines to be described below.

One limitation of all radiant heating tunnels should, however, be borne in mind, viz. that all the surfaces being heated must be more or less directly exposed to the radiating surfaces. This means that although the rate of heating may be speeded up five- or ten-fold, in some cases, as, for instance, when awkwardly shaped parts are concerned, the oven loading may well be less for a given space and conveyor

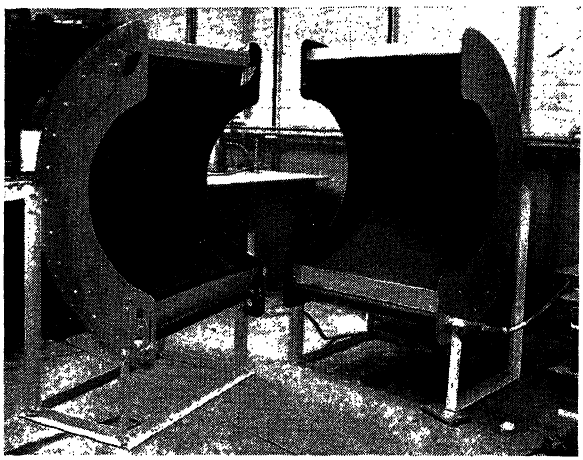


Fig. 26.—Experimental Gas-heated Paint Stoving Unit (open)
(Courtesy Gas Light and Coke Co., Ltd.)

speed than when a normal convection oven is employed. This loss in oven capacity has to be weighed against the advantages to be gained by the shorter time of actual stoving in each particular case in order that a decision may be reached as to whether a radiant heating plant is to be economical.

Medium Temperature Unit—A type of medium temperature unit described by the above authors and shown in Figs. 26 and 27, consists of a cylindrical tunnel split in two halves. Each half is made from curved steel sheets 5 ft. long by 3 ft. wide, the sheets being bent to give practically a semi-circular cross-section of about 16 in. radius. Behind each sheet, which serves as the radiating surface, is an insulating refractory back leaving a tapered space between the sheet and the refractory of $3\frac{1}{4}$ in. at the bottom and $\frac{1}{4}$ in. at the top. A bar burner with standard luminous jets which give a highly efficient rate of heat transfer to the radiating panel, is situated at the base of the tapered spaces, the products of combustion passing out at the top with a CO_2 content of about 8 per cent. The advantages of using luminous jets are two-fold. In the first

place, there is no risk of clogging of air intakes, and, secondly, heat transfer from correctly designed luminous flames to a medium temperature radiating sheet will take place more efficiently than when non-luminous flames are employed owing to the good radiating properties of the incandescent carbon particles present in luminous flames.

An average temperature of about 650° F. is aimed at for the blackened radiating steel sheet, and in order to promote uniformity of temperature,

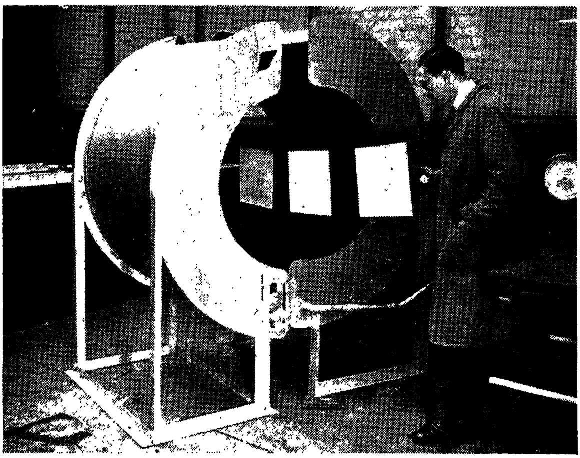


Fig. 27.—Experimental Gas-heated Paint Stoving Unit (in operation) (Courtesy Gas Light and Coke Co., Ltd.)

the bottom part of the inside of the panel is protected by an inner sheet giving an air-space of about $\frac{1}{4}$ in. To facilitate heat transfer at the top the radiating panel is ribbed on its face with ribs $\frac{3}{16}$ in. deep and spaced $1\frac{1}{4}$ in. apart. These units can be built up to give tunnels of any length.

Heat Distribution.—Measurements taken on the radiating face in the middle of a 3-ft. section of tunnel gave a temperature of 645° F. in the upper zone, 685° F. in the middle, and 650° F. in the bottom zone. This shows a satisfactory degree of uniformity of temperature of the surfaces. The measurements were taken by means of blackened thermocouples bolted on to the face of the panels. The spectral distribution of the energy given out by this medium temperature panel as compared with the electric radiant heating lamps and the high temperature panel (see p. 57) is shown in Fig. 28.

The total flux density was measured in a vertical plane between the two panels by means of a water-flow calorimeter with lamp-blacked front and back surfaces 6 in. square and all other surfaces and edges

protected by aluminium foil. The total flux was 2,900 B.T.U.'s per sq. ft. per hour falling on each side of the calorimeter, equivalent to 6 watts per sq. in. This is to be compared with the $2\frac{1}{2}$ to 4 watts per

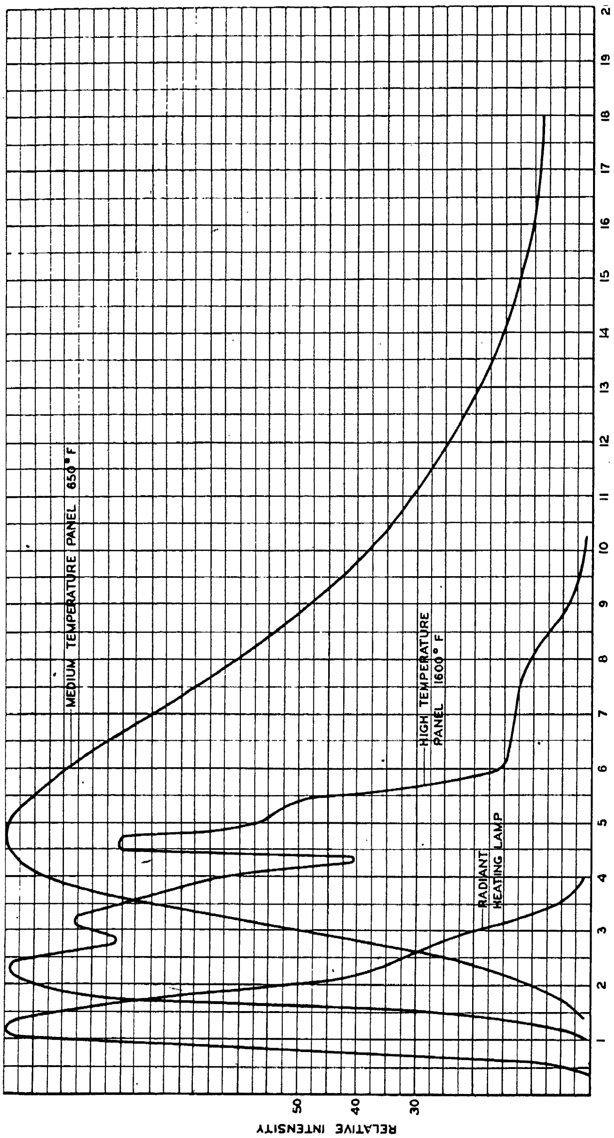


Fig. 28.—Spectral distribution of energy from different radiant heat sources

sq. in. obtained in the average tungsten filament lamp plants such as are in present-day operation. The maximum rating claimed for such electric plants does not exceed 5 watts per sq. in., on each side of a

panel in the centre of the unit. Since 1 watt per sq. in.=490 B.T.U.'s per sq. ft. per hour, flux densities prevailing in electrically operated plants are equivalent to about 750 to 1,500 B.T.U.'s per hour. The gas plant described above thus has a higher rate of heat emission than

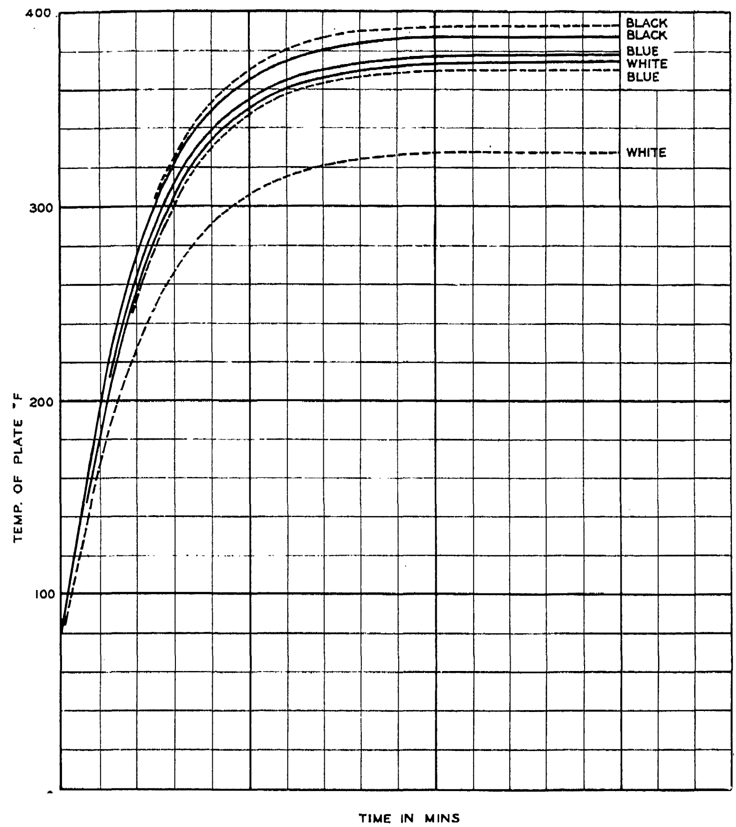


Fig. 29.—Comparison of heating ratio of electric lamp and medium temperature gas panel for different coloured paints

the electric plant and tests show that proportionately higher rates of paint stoving can be obtained than with the latter.

Table V gives the rate of heating-up of sheet metal plates in a gas-heated tunnel of this type. It is interesting to note that these results compare favourably with those shown in Fig. 8 for electric lamp heating. The influence in performance as between gas and electrical equipment is illustrated in Fig. 29, which shows the rate of heating-up, and the final temperatures attained in the case of black, white and blue painted sheets respectively.

TABLE V

HEATING OF SHEET METAL PLATE 12 IN. BY 12 IN. S.W.G. 22 AND 12 IN. BY 5 IN. S.W.G. 9 IN MEDIUM TEMPERATURE TUNNEL

	Temperature : °F.	
Time.	S.W.G. 22.	S.W.G. 6.
0 secs.	70	70
10 ,,	140	—
15 ,,	175	85
30 ,,	240	100
45 ,,	300	114
1 min.	335	130
1½ ,,	390	160
2 ,,	410	195
2½ ,,	425	225
3 ,,	430	250
4 ,,	—	290
6 ,,	—	344
8 ,,	—	390
10 ,,	—	417

Practical paint-drying tests showed that white synthetic refrigerator paint on a steel plate of S.W.G. 22 and 1 ft. square was stoved in three minutes in the case of the priming coat and in less than two minutes in the case of the finishing coat. In two and a quarter minutes there was evidence of deterioration in the gloss of the finish. A convection oven with an air temperature of 350° F. took thirty minutes to dry the primer and sixteen minutes to dry the finishing coat when the plates were protected from direct radiation from the sides of the oven.

It is of interest to note that in a direct fired convection oven a temperature of 590° F. was needed to dry the primer in three minutes and the finishing coat in one and three-quarter minutes when the plate was exposed to radiation from the walls of the oven. On the other hand, when the plate was protected from wall radiation by polished aluminium plates the corresponding temperatures were 720° F. for the primer and 700° F. for the finishing coat.

Petrol containers of sheet steel of 19 S.W.G. coated with buff-coloured oil-modified synthetic resin paint were dried in five minutes, as compared with thirty minutes in a direct fired oven at 350° F. with the can shielded from radiation. At an air temperature of 590° F. drying was

completed in four minutes with the can exposed to the wall radiation, and at 710° F. with the can protected from radiation. Plants based on this design are giving satisfactory service in production.

High Temperature Units.—By the use of high temperature radiating surfaces much higher flux densities can be obtained, and more radiation is emitted in the visible part of the spectrum.

In one type of unit, i.e. the surface combustor, an air-gas mixture is burnt on the surface of a porous refractory panel. The radiating surface is incandescent and is capable of giving flux densities of up to 40,000 B.T.U.'s per sq. ft. per hour (more than 80 watts per sq. in.) if the object is completely surrounded by the combustion surface. High energy densities are essential when coatings on heavy metal parts, such as castings, are to be baked by radiant heat if any considerable reduction in stoving time is to be obtained. The stoving times obtainable with the electric bulb type of plant or even with the medium temperature gas plant, described above, are apt to be somewhat long. Thus varnish on a 15-lb. roughly cylindrical hollow casting with an overall length of 12 in., and a maximum diameter of 4 in., and having a wall thickness of ½ in. took forty-five minutes to cure (as opposed to two hours in a convection oven at 350° F.).

Andrew and Chamberlain also describe an alternative type of panel consisting of vertical refractory rods spaced in front of a refractory back, the space between the rods and the back being tapered. The products of combustion pass up this space from a luminous bar burner. These panels are operated vertically, but can be used either upwards or downwards until the angle is within 15° of the horizontal when facing downwards, or 45° when facing upwards, and are capable of giving a maximum flux density of 25,000 B.T.U.'s per sq. ft. per hour. The major part of the energy is radiated at between 15,000 Å and 60,000 Å, the radiant efficiency being approximately 35 per cent.

The 15-lb. casting previously mentioned was raised from 70° F. to 350° F. in six minutes, as compared with thirty minutes in the medium temperature panels. This was obtained by using only a single pair of panels, each 104 sq. in. in superficial area, so that there is little doubt that heavy end losses occurred.

With energy sources of this kind, however, there is the disadvantage that it is more difficult to obtain a uniform distribution of radiant energy on the parts being heated owing to the difficulty of conforming the shape of the radiating elements to suit the parts being dried. This is particularly important in the case of high-temperature sources, since such high energy densities make it much more difficult to avoid local overheating if the radiation density within the oven is uneven. As opposed to this, however, the relatively good heat conductivity of metals

tends to even out the heat distribution in metal parts of heavy section for which the high energy density units are most likely to be employed.

High energy density radiant heating units are already being successfully employed for the rapid drying of varnishes on heavy castings.

Gas Burners.—Radiant heat gas burners have also been described giving high energy outputs. Normally the problem of utilising radiant heat from a flame is a difficult one. Certain flames are better radiators than others; thus, for example, gas flames rich in methane are known to be good radiators.

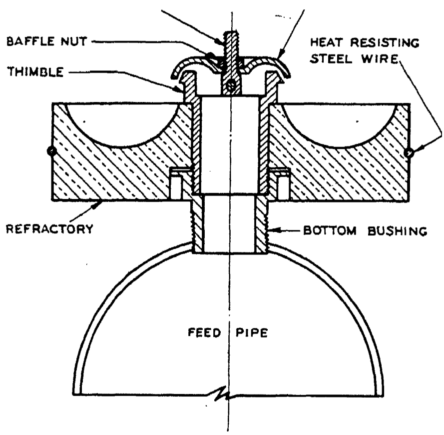


Fig. 30.—Section of the Burdett burner

Gas radiation can be classified into two main types:

(*a*) Heat radiated by solid carbon particles suspended in the flame, and

(*b*) Radiation from the hot gases themselves which takes place even in the absence of actual combustion.

Of these gases carbon dioxide, steam, carbon monoxide, and the hydrocarbons are the most important. There is practically no radiation from hydrogen, oxygen, and nitrogen; carbon monoxide is a poor radiator. In fact, it has been shown that the heat radiated from a non-luminous (bunsen) type of flame is almost entirely due to the radiating properties of the carbon dioxide present in the products of combustion.

When radiant heat transfer from a non-luminous flame is required it is therefore best to make the flame impinge on to a refractory surface to facilitate the maximum utilisation of the energy content of the burning gases. One radiating unit of this type is the Burdett burner. This burner (Fig. 30) consists of an alumnite refractory disc which burns a controlled air-gas mixture fed to it by a mixing valve and a

low-pressure blower. There is no separate combustion chamber, combustion taking place in the concave refractory disc, so that both

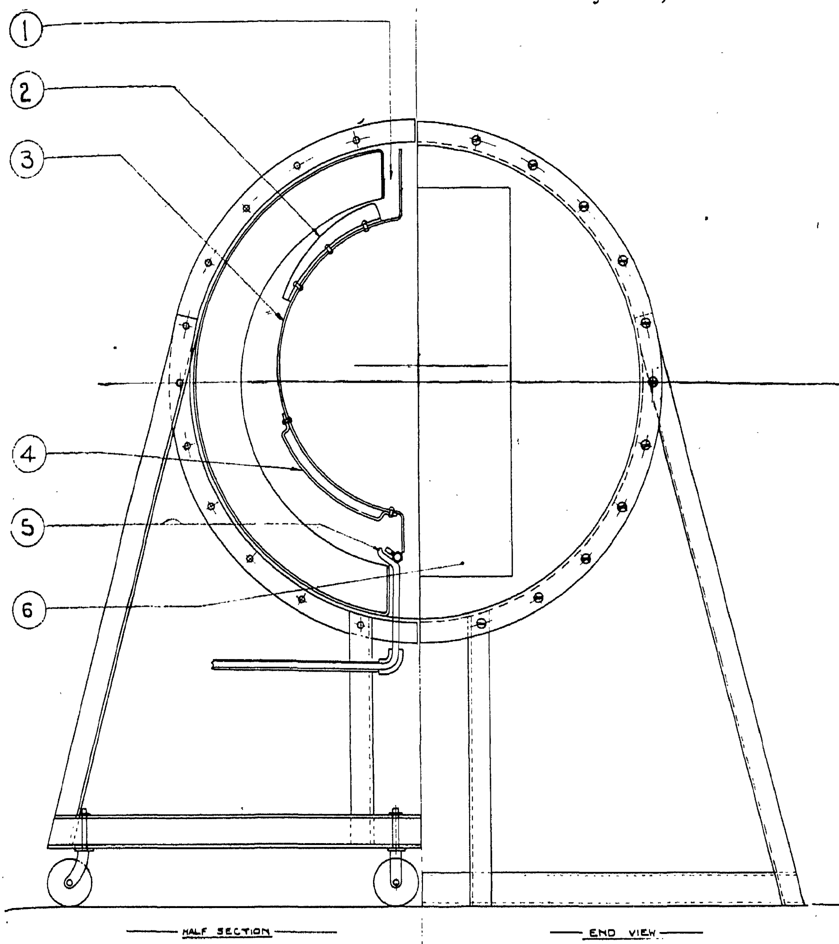


Fig. 31.—General arrangement of a conveyor gas-fired radiant heating oven. (Courtesy of Joseph Lucas, Ltd.)

(1) Outlet to flue (2) Heat retaining ribs
(3) Radiating panel (4) Deflector plate
(5) Gas burner (6) End opening

convected and radiated heat are made full use of. The refractory disc operates at a temperature of 2300° F. The disc sizes available range from $2\frac{1}{2}$ in. to 12 in. in diameter with gas consumptions of 10,000 to 320,000 B.T.U.'s per hour.

Advantages of Gas Installations.—There are many advantages

which gas-operated units have over electric plants. In the first place, they are simple to construct, and are more robust than electric lamp units. The cost of construction is also, generally speaking, much lower, owing to the absence of expensive reflectors, electrical switch-gear, and bulbs.

Whilst electrical units have a radiating efficiency of over 80 per cent when the reflectors are clean, this is quickly reduced as the reflectors tarnish. The lower thermal efficiency of the gas radiators is compensated for by (*a*) the lower cost of gas and (*b*) the fact that convection losses are more readily controlled in a gas plant without risk of damaging bulbs or holders, which tends to occur in electric plants if the temperature within the oven becomes unduly high.

Gas plants have, so far, the great advantage that very much higher energy densities can be employed, as has already been described and, moreover, these energy densities can be regulated readily by simply opening or closing the gas valve. Electrical plants are much more difficult to regulate. Moreover, bulb failures often reduce the efficiency of the plant during its operation, and this can only be rectified by stopping the unit and replacing the bulbs, an operation which may take up valuable time.

In the opinion of the present authors the potentialities of gas-fired radiant heat paint-baking ovens are very great indeed, and they may well eventually supersede the present electric bulb type of plant. The main cause of the present-day ascendancy of the latter is that for one reason or another electrical installations have obtained a flying start in this field.

CHAPTER VI

PAINT FORMULATION

Radiant heat drying differs in several fundamental aspects from the normal convection method. So far as paint formulation goes there are two essential factors that are important:

(*a*) the rate of heating up of the paint film is generally far more rapid than by conventional methods;
(*b*) the duration of the peak temperature is relatively short.

It is not possible here to enter too fully into the fundamental aspects of paint chemistry, but as the success or failure of paint-drying by radiant heat (or, indeed, by any other method) is dependent to a considerable extent on the nature of the paint used, the subject merits some consideration.

Paint Constituents.—A modern paint or varnish is compounded essentially of the following constituents, some or all of which may be present:

(*a*) A "drying" oil, i.e. one which hardens by polymerisation or by oxidation; the hardening process is generally a combination of these factors and may take place with or without the application of heat. These bases are usually natural oils, often processed in various ways before their incorporation in the paint. Typical examples are linseed oil, china wood oil, perilla oil and dehydrated castor oil.
(*b*) An oil-soluble resin constituent; these resins may be of the thermo-setting type, e.g. by phenol-formaldehyde, urea-formaldehyde, and glyceryl-phthalate resins, or they may be natural gums "run" with the oil (e.g. copal gum).
(*c*) A dryer, for accelerating the hardening of the paint film. The metallic soaps (such as lead or maganese oleate, for example) represent the most important group of these driers, which probably function catalytically.
(*d*) The thinner or vehicle which is used as carrier for the above-mentioned paint constituents and facilitates the application of the paint by spraying or brushing. Usually mixtures of solvents are applied to secure a satisfactory drying rate; sometimes the constituents of the vehicle are not true solvents when employed individually but the mixture gives a suitable solution of the paint oils. Such non-solvents are often termed diluents.

(*e*) A plasticiser, e.g. a high-boiling organic compound such as tricresyl phosphate or dibutyl phthalate, to increase the elasticity of the paint film.

(*f*) A pigment is included in paints (other than lacquers) to give colour and opacity to the resulting film. The pigments may be natural mineral colouring materials or they may be synthetically produced by the absorption of organic dyestuffs on mordant bases such as activated alumina. The pigments may be relatively inert substances such as titanium dioxide or they may have a considerable effect on the setting of the paint themselves, as is the case with zinc oxide.

For radiant heat drying to be most effective the paint should be "tailor-made" to meet the special characteristics of the radiant heat process. Most paints (other than cellulose lacquers in which drying is complete when the solvents have been driven off) contain drying oils and heat-polymerising resins, and it is in the finishing of the latter that radiant heating is most useful.

Drying Oils.—All drying oils "set" by combined oxidation and polymerisation although in some oils the greater part of the hardening process may take place as a result of oxidation rather than polymerisation and vice versa, depending in part on the method of drying. By polymerisation is meant the agglomeration of large numbers of relatively small molecules into extremely large molecules. This process is usually accompanied by a thickening and hardening of the material, and is accelerated by heat. Oxidation is a comparatively slow process in comparison with polymerisation and is not accelerated by heat to the extent that polymerisation is. For the rapid drying to which paint is subjected by the radiant heat process an oil which will harden by polymerisation under the influence of rapid heating rather than by oxidation is therefore desirable. Tung oil is a valuable natural oil ingredient from this point of view, but in general more than one drying oil is used in a paint formulation in varying proportions as it is found that such admixture exercises a favourable influence in the production of a hard finish. Drying oils are commonly "boiled" or pre-polymerised before incorporation in a paint; such "stand-oils" as they are called produce a much more durable film than do the natural oils.

Stand-oils require driers to promote hardening in a reasonable space of time. These driers, however, also tend to favour oxidation hardening rather than polymerisation hardening unless rapid heating of the paint film can be brought about. Thus highly pre-polymerised stand oils are very desirable as ingredients in paints for radiant heat drying. Dehydrated castor oil is an extremely useful ingredient in the synthetic

resin varnishes, as although it does not attain the hardness of linseed oil or tung oil films when dried alone, this is not the case when it is included as a constituent of oil-modified synthetic resins, so that excellent films result.

Oil-Modified Synthetic Resins.—It is here that the value of the synthetics appears inasmuch as they are very rapidly polymerised by heat; the most satisfactory paints for radiant heat drying are therefore largely based on oil-modified synthetic resins. Both the urea and the glyceryl-phthalate resins, e.g. glyptal, are better than the phenol-formaldehyde type as they are more rapidly hardened than the latter, and are therefore extensively used. The alkyd resin group (of which glyceryl-phthalate is a typical example) are polymers produced by the condensation of a polyhydric alcohol and a polybasic acid (e.g. glycerol and phthalic acid). The condensation process has to be carried out in the presence of a drying oil which must be introduced into the alkyd complex in order that the product may be soluble in the vehicle and be suitable for paint purposes. Owing to the extreme reactivity of the alcohol-acid mixture, however, rapidly gelling of the complex occurs unless special precautions are taken to inhibit this primary reaction and enable the drying oil to enter the complex. This can be done by making use of the fatty acid of the drying oil (as a constituent of the reaction mixture) and by other methods. The aim, in any case, is to produce a highly complex molecular structure which can be heat-polymerised with rapidity. The manufacturing conditions are very widely variable and the characteristics of the polymer depend as much on these as on the relative proportions of the constituents.

The oil-modified alkyd resin polymers are characterised by the high durability and excellent resistance to ageing of the varnish films produced from them. The most striking advantage of the alkyd resins in varnishes is noted when they are compared with natural varnish gums. Such gums retain their brittleness and hardness in the oil, so that the durability of the final varnish film is largely proportional to its oil content, varnishes with a low oil content being extremely poor. With an alkyd resin, however, durability is much less affected by the oil content.

Characteristics of the Alkyd Resin Varnishes.—Thus Siddle ([19]) gives the following approximate comparisons between alkyd resin varnishes and oil varnishes of the orthodox type. Linseed oils alkyds containing 60, 50, and 40 per cent oil respectively approximate in flexibility to an orthodox varnish containing 85, 80, and 75 per cent oil respectively. The retention of that flexibility on ageing is considerably better in the case of the alkyd than the oil varnish. Also a typical linseed oil alkyd containing 35 per cent oil has approximately the drying-time

of an orthodox varnish containing only 15 per cent oil, yet on durability it is better than a 75 per cent oil-natural resin composition. The practical significance of this is that whereas in an orthodox varnish a compromise in durability with drying-time or other film characteristics is necessary, with a correctly made unadulterated alkyd the durability characteristics can be neglected as a factor in influencing oil-length.

Siddle's conclusions regarding durability are probably not typical of all conditions. Certainly natural oil varnishes can be produced, the life of which will compare more favourably with that of synthetic finishes than has been suggested above, although their drying-time will be rather longer. Where rapid-drying industrial finishes are concerned, however, the use of synthetics has decided advantages.

Air-drying paints can also be satisfactorily dried, the temperatures in this case not exceeding 150° F.

Lacquers, drying by the evaporation of solvents, are treated at similar temperatures; chlorinated rubber paints may also be successfully dried in an extremely short length of time.

Solvent Balance.—Solvent balance demands more careful attention than with paints designed for convection ovens. The very rapid heating of the metal means that the solvents should be neither of too high nor too low a volatility. The solvents are to a considerable extent volatilised at room temperature in the few minutes which are allowed to elapse between the spraying operation and the time when the parts are put into the oven. The final traces of solvent are then quickly removed by the heat. If the solvents are of the quickly volatilising type there will be a tendency for bubble and blister formation or pinholing to occur in the paint, which may set before the solvents have had an opportunity to escape. On the other hand the total heating-time is generally so short that not all the solvent will have had time to escape before the end of the drying cycle, if an excessive proportion of higher-boiling constituents is present.

Where the paint formulation is incorrect or the heating-time too short, incomplete polymerisation will take place and subsequent hardening will depend on a slow oxidation process in air. Such paint films may appear quite dry to the touch, but will not usually withstand scratching by the thumbnail. Even when slow air-hardening has taken place after a considerable period the resulting paint film will not have the durability of a properly heat-polymerised enamel. Similar considerations apply to finishes which have been stoved at too low a temperature, as will be mentioned later.

Driers.—Driers carefully incorporated can help to reduce the drying time, but must be used with circumspection to prevent crinkling of the surface. In certain cases, however, a crinkled surface is aimed

at, crinkle lacquers being useful for the finishing of cast metal parts, for example, and active drying accelerators are useful in producing this effect. The soft lacquer remaining below the thin, rapidly dried, surface skin then assumes the characteristic appearance of this type of finish.

Colour.—Colour also naturally plays a more important part with radiant heating than is the case with convection heating. Clearly, a light coloured surface reflects a considerable proportion of the incident radiation whilst a dark colour absorbs it. Whether the surface is glossy or matt is of no consequence since the total energy absorption does not appear to be greatly affected.

An investigation by H. L. Beakes ([20]) showed that the infra-red absorption of paint pigments ground in similar vehicles could be arranged in the following order of decreasing absorptivity: carbon black, iron blue, chrome green, chrome yellow and white, the last two being very close together. A very small addition (0·1 per cent) of blue to the yellow was sufficient to increase the heating rate considerably. Reds were more absorptive than yellows but less so than dark greens. A small amount of black added to white greatly increased the absorption rate.

Much depends on proper coverage of the base metal since the reflectivity of the latter if the hiding powers of the paint are not good will make the results most disappointing. For this reason the drying of transparent types of coatings on reflecting metal surfaces demands very special attention.

The importance of colour must not be exaggerated, however. There is a tendency sometimes to believe that owing to the reflective characteristics of light colours they are not suited to the radiant heat drying process. This is emphatically not the case, for two reasons: firstly, in a well-designed unit radiation diffused by the paint will appear as effective heat within the oven so that from the efficiency point of view losses should not be excessive, as has already been stated.

Secondly, a loss in drying-time due to a lowered rate of heat absorption due to the pigment colour can be compensated by a modification in the paint formula. The use of oil-modified resins enables a high degree of pre-polymerisation to be obtained actually during the course of manufacture of the material by modern paint production technique. Such synthetics are then dispersed in the paint medium and a relatively small energy input will complete their conversion.

Dispersion.—Dispersion presents many problems of its own; especially when pigments have been introduced. The gellation which sometimes occurs with particular pigments can be removed by the use of peptising agents, such as salicylic acid.

Polymerised drying oils are much better dispersing agents than raw oils, and should therefore be employed. On the other hand dehydrated castor oil is not so satisfactory for the dispersion of pigments.

Energy Requirements for Drying.—For any particular paint based mainly on heat-polymerising constituents a definite energy input is required for complete hardening. The rate of oxidation and polymerisation depends both on the time and temperature and generally speaking the higher the temperature the shorter is the drying-time. At low temperatures the finish takes a long time to harden, and moreover a higher proportion of oxidation hardening may take place than polymerisation hardening with the result that a finish of poorer durability will be obtained. With synthetic based enamels it is therefore probable that a better finish will be produced because of the higher temperature attained with radiant heat. The acceleration of the drying rate has limitations, of course, in that the temperature must not be too high in relation to the absorptive capacity of the paint or burning may occur. Such carbonisation might be caused by a particular range of wavelengths which are preferentially selected from the radiation emitted by the tungsten lamps. The result is that superficial overheating can occur before the paint has dried. It is here that a study of the absorption characteristics of paints can be usefully made; the inclusion of a suitable filter in front of the lamp might then effect a substantial improvement in the rate at which drying could be carried out without discoloration. In the present state of our knowledge of the subject, such studies are only beginning to be made, but when further progress in this direction has been achieved the results will obviously be of great practical importance.

Limitations of Paints.—Burning, however, is unlikely in present-day plants unless the paint is of an entirely wrong type for radiant heat baking—such as one based on poor quality natural drying oils.

Temperatures of 350° F. are not often exceeded although with dark-coloured paints where discoloration is of less importance there is no reason why temperatures as high as 450° F. should not be usefully employed. In a convection oven the air temperature is maintained at a pre-determined value and it is doubtful whether in many cases the paint surface reaches the requisite stoving temperature. With radiant heating the paint rapidly attains the drying temperature despite the fact that the air temperature may be considerably lower.

As regards the electric-bulb type of plant, at any rate the lower limit of the drying-time of the paint is more likely to be determined by the heating capacity of the unit than by the paint formula. The reason is that with the practical limitations of lamp size and reflector design the amount of radiation which can be directed on to a specific

area of surface cannot be conveniently increased for a given oven size beyond a fairly well-defined amount. This is at present of the order of $2\frac{1}{2}$ to 4 watts per sq. ft. of surface. Increasing the dimensions of the oven beyond a reasonable limit introduces other obvious disadvantages so that this method of adding to the rate of heat input cannot be carried too far. These considerations apply equally to conveyorised or batch type ovens.

In one respect, however, this statement should perhaps be qualified and that is so far as colour is concerned. Excessively rapid rates of heating can darken the shade of light enamels and where colour is important the heating-up rate must be regulated so that this is avoided unless modifications can be made to the paint to meet the rate of energy input. Darkening of the pigment is more likely to occur where organic pigments are employed; mineral or inorganic pigments are not so subject to this effect.

Pigments.—The subject of paint pigmentation is a very complex one and does not, generally speaking, present any problems specifically related to infra-red drying methods; the normal pigments and pigmentation operations prove entirely satisfactory under infra-red drying conditions apart from the points already mentioned. White is naturally the most highly reflecting colour and as such will tend to be more difficult to heat up than the lighter colours. This can be overcome in some cases where thin metal parts are being treated and the shape of which is suitable, by heating the reverse side of the metal if the latter is bare or covered with a paint of darker colour.

The blues and greens are good absorbers of radiation; red on the other hand is a good reflector in the infra-red range and is therefore difficult to dry. The variation on the reflecting characteristics of various pigments with different wave-lengths of incident light are given in Table VI.([21])

A characteristic of a number of paints is a phenomenon akin in some respects to thixotropy. It is exemplified by the paint remaining in a somewhat soft condition on emerging from the stove even when it has cooled. On standing for several hours it then hardens. This may be due to physical changes taking place within the paint film relatively slowly until the ultimate hardness is reached. This makes the handling of the painted surface troublesome for some little time after it has emerged from the oven, but if damage can be avoided during this stage the finishes prove entirely satisfactory. Sometimes an improvement can be made by introducing a cooling chamber with a forced draught after the oven, since rapid cooling seems to accelerate the hardening of the paint film.

TABLE VI

Percentage Reflectivities of Typical Pigments for Radiation of Different Wave-lengths

Pigment.	Wave-length (Ångstroms).			
	6,000	9,500	44,000	88,000
Cobalt oxide, Co_2O_3 (grey)	3	4	14	13
Chromium oxide, Cr_2O_3 (dark green)	27	45	33	5
Lead oxide, PbO (yellow)	52	—	51	26
Ferric oxide, Fe_2O_3 (red)	26	41	30	4
Lead chromate, $PbCrO_4$ (yellow)	70	—	41	5
Alumina, Al_2O_3 (white)	84	88	21	20
Zinc oxide, ZnO (white)	82	86	8	3
Magnesia, MgO (white)	86	—	16	2
Lead carbonate, $PbCO_3$ (white)	88	93	29	10

CHAPTER VII

THE FIELD OF APPLICATION OF RADIANT HEATING

Up to the present radiant heating has had its most conspicuous successes in the stoving of finishes on sheet metals, but many attempts have also been made to extend the success to other fields. Thus for example the drying of impregnated armatures and field coils has been tried but so far this type of application does not seem to have met with anything like general approval. This may be partly due to the difficult nature of the heating problem involved, but is certainly, to a large extent, due to the use of the open type of oven and the low available energy densities.

The theoretical treatment given above has shown how important both these factors are, and makes it essential to consider the effects of a considerable increase in the available energy densities before any true picture of the possible field of application of radiant heating can be given. The method of application of radiant heating can in fact be divided into three classes:

(*a*) Low energy density and enclosed ovens.
(*b*) Any energy density and open units.
(*c*) High energy density and enclosed ovens.

Enclosed Ovens.—(*a*) The first is the method at present mainly in vogue for sheet metal articles of large area-mass ratio. These can far better be stoved in an enclosed oven and there is no reason, in most cases, for not designing such ovens. Broadly speaking the main limitations of this class of application are temperature and quantity of heat. The temperature of the work should not be too high and it should not use too great a quantity of heat to attain it. As both temperature and quantity of heat rise so will the control of the air-flow become more important. Some air-flow must be permitted when drying finishes and evaporating solvents, but one could envisage simple heating applications, which would require no air-flow. In these cases suitably designed radiant heating ovens could be constructed using the equipment at present available.

It is usual to consider the finishing temperature attainable by radiant heating to be approximately 600°F.; but this temperature would be rather high for present-day equipment, or at least would require the use of a very high energy density. With the usual open

type of stove a figure of between 300° F. and 400° F. would probably be an economic limit. There is no doubt that with the use of more power higher temperatures could be attained, but the waste of energy would be considerable. On the other hand the enclosed type of stove with a reflecting interior should give 600° F. as a reasonable limit.

Open-type Ovens.—(*b*) In spite of the inefficient nature of the process, there do occur cases where the use of open units is justifiable on the grounds of flexibility. The original use of radiant heating,

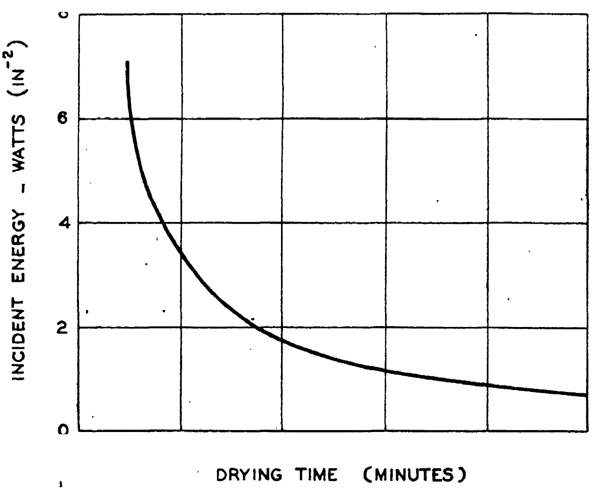


Fig. 32.—Relation between drying-time and incident energy density requirements for the evaporation of a water film from metal parts

namely touching up of blemishes on a painted surface, can be applied to small articles as well as large. A single radiant heating lamp on a bench may prove a very great help, and obviously for such a job there can be no question of a well-designed oven! Also water-wet parts may be dried by radiant heating lamps when the amount of water to be evaporated is small. In fact there may prove to be many local heating jobs that can be done by the radiation.

The drying of water-wet parts and the touching up of painted articles are just two examples of successful applications of radiant heating under very inefficient conditions. The power requirements of the former are shown in Fig. 32. These applications are in reality only apparently inefficient, since the time and labour that would be involved to turn them into efficient engineering applications would be uneconomic. If the process gives a service that is worth while the question of its being inefficient from a scientific point of view is not important.

High Energy Density Plants.—(*c*) The advent of higher energy densities and more robust sources of radiation may be expected to increase the field of application of radiant heating very considerably. The drying of armatures and field coils after impregnation with varnish has already been mentioned. This does not seem feasible with the low energy densities at present available, but fair results have been obtained by the use of the ordinary electrical bar-heater element, mounted in a

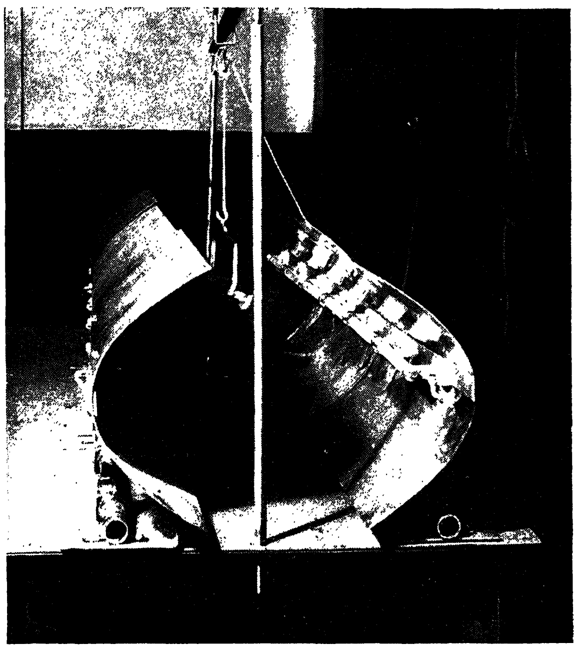


Fig. 33.—Experimental stoving unit using bar heaters
(Courtesy of Joseph Lucas Co., Ltd.)

suitable cylindrical reflector, as exemplified by the experimental unit shown in Fig. 33.

There seems, in theory at any rate, no reason why the maximum temperature attainable should not be very considerably increased, and it is certain that the use of high energy densities will permit of the treatment of far more massive articles than hitherto.

Future Trends.—The problems to be encountered in the design of radiant heating bulbs should not be minimised, but there seems no reason why the limiting temperature should not be raised to 600° C. (1112° F.) using anodised aluminium reflecting surfaces and hard glass sealed beam radiant heating lamps. The problems to be encountered at temperatures about that of the melting-point of aluminium are both technical and financial.

The main source of energy which has been discussed in this account of radiant heating has been the electric lamp. It has been shown that the method of applying the heat to a finish is of no consequence and only the temperature-time relation is important. Further it has been stated that on occasions practices, which appear theoretically unsound, are in fact economic, e.g. the drying of water-wet parts. The same

Fig. 34.—Sheet steel petrol container, with red painted interior and buff exterior. Both painted surfaces were dried simultaneously in five minutes in a gas-fired medium temperature radiant heating stove

may be true of the source of radiant energy. In his original work Groven describes how he tried a heated iron wire as a source of radiation and found that it was not satisfactory. Maxted ([22]) has shown conclusively the superiority of the enclosed filament as a radiator, and finally the knowledge that a vacuum electric bulb will radiate 92 per cent of the energy input should leave no doubt that the electric lamp is the most efficient radiator. This, however, does not necessarily mean that it is the most suitable heater in all cases. Thus in the field of domestic heating the electric bar element in a cylindrical reflector is very common. This is, in fact, a form of radiant heater, but there are many people who are of the opinion that the same power devoted to heating and circulating the air will result in more pleasant conditions.

There are in fact some fields when radiation is not the most suitable method of transferring heat, and if this is the case these will almost certainly be fields in which both radiation and convection are desirable. For this reason the use of the electric bar heater element in a cylindrical reflector is worthy of attention. The present circumstances impose such severe handicaps on development of new equipment that it may be that the high energy densities attainable by this type of unit combined with its compact nature will make this source of radiant heat economic for some applications.

The more recently developed gas-radiators, which have been described above, may be expected to open up a widening field for the

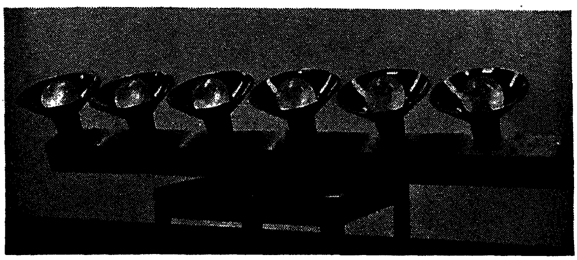


Fig. 35.—Bank of Radiant Heating Reflectors
(Courtesy of the British Thomson-Houston Co., Ltd.)

use of radiant heating. The size is by no means limited to that of the particular example shown, and one can easily visualise a range of units from a small bench heater to assist in drying touched-up parts to an installation capable of taking a complete motor-car. Two factors will tend to help in extending the range of industrial applications for which radiant heating is partially suitable. These factors are (*a*) the uniform distribution of radiant energy with regard to both direction and position which can be obtained, and (*b*) the ease with which high energy densities can be secured, particularly with gas-fired equipment.

Gas *v.* Electricity.—The simplicity and cheapness of the gas-plant coupled with its power will again help to favour its use. The straightforward and simple method of working is the result of careful design and not of haphazard methods. Complexity of construction and design is not always a hall-mark of efficiency in a plant! Whether industrial experience will show that gas can give the clean working conditions and reliable operation possible with electrical equipment remains to be seen. There is, however, one aspect of cleanliness that deserves attention and that is the question of the fumes given off by the articles being stoved. The fact that these are often allowed to pollute the atmosphere of the factory in which the plant is installed is a most undesirable feature of some plants. The necessity for controlling the products of combustion

may lead to improved conditions with gas-plants from this aspect also.

The "price of power" argument is not itself conclusive evidence in favour of gas operation. It is, however, a very welcome feature, which combined with the inexpensive nature of the plant, will tend to favour gas operation when other circumstances are similar.

It can be said with little fear of contradiction that for the baking of

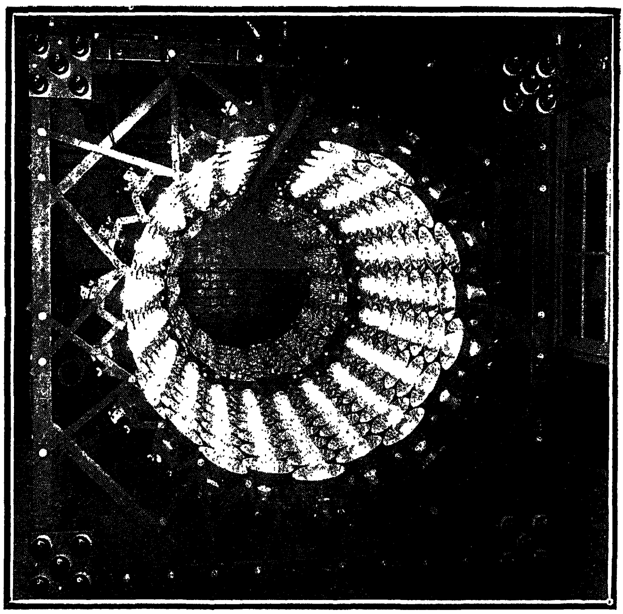


Fig. 36.—Experimental "infra-red" tunnel
(Courtesy of the British Thomson-Houston Co., Ltd.)

paints and enamels on most sheet metal articles the purely convection type of oven is obsolescent, though certain uses may prove economic owing to peculiarities of design. The whole field of industrial heating would seem to be open to radiant energy, though in a very large number of cases the simultaneous effects of convection and conduction will still be of equal importance and merit careful control. It would probably be correct to say that in many applications heat transfer has to a large extent been by radiation although the design of oven employed has not been favourable to the transfer process. Many plants might well be redesigned to facilitate the transfer of heat by radiation. In some cases such changes will be small, but the results may be of great practical value.

In this account of radiant heating an attempt has been made to

show the fundamentals of the subject and how ideal solutions are being adjusted to practical requirements. The industrial use of radiant heat is too new for final judgment on any point, either in choice of power at one end or formulation of finish at the other. The subject has, however, reached a stage where planned development is possible.

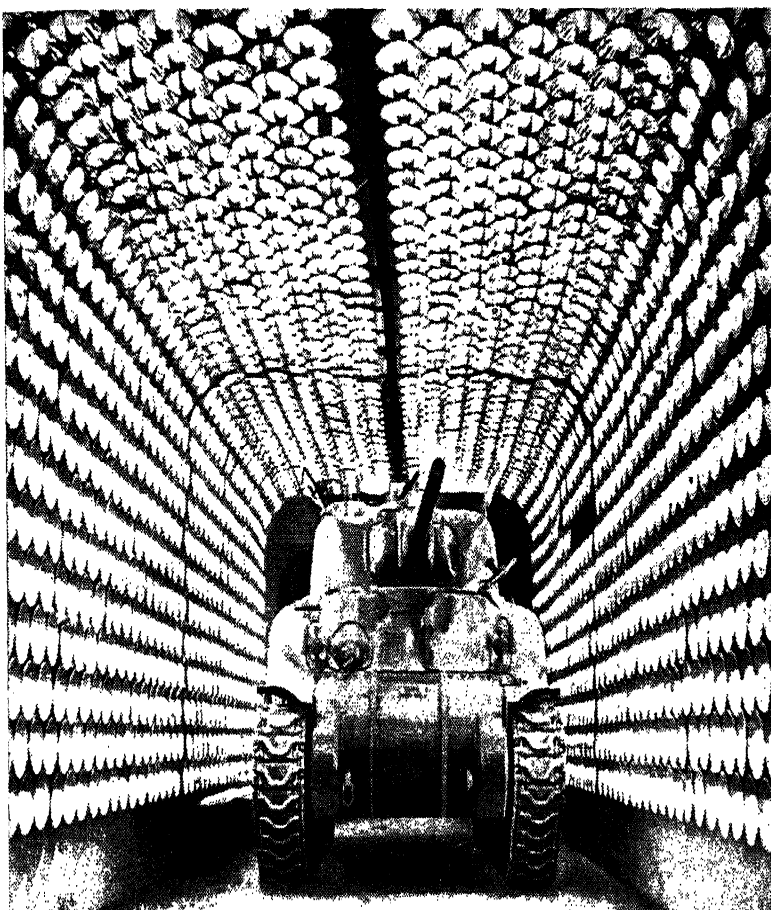


Fig. 37.—An American radiant heat stoving installation showing the drying of paint on a tank. This is accomplished in four minutes
(Courtesy of The Associated Press)

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